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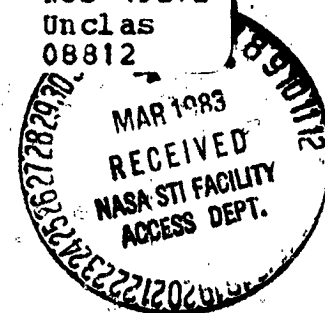
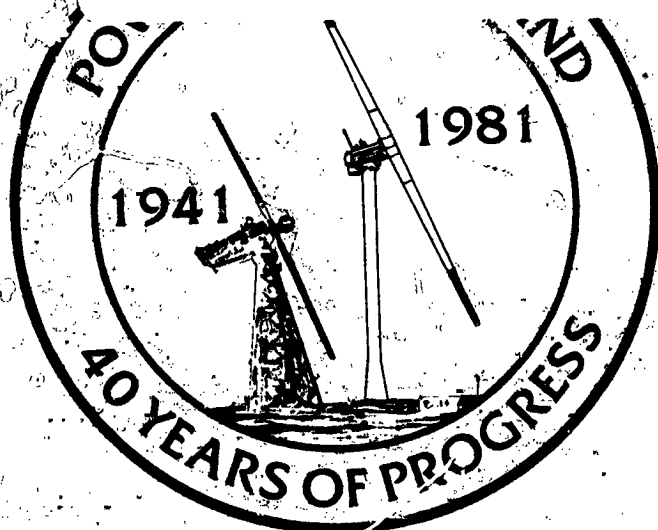
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# Large Horizontal-Axis Wind Turbines

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# Large Horizontal-Axis Wind Turbines

*Robert W. Thresher, Editor  
Oregon State University  
Corvallis, Oregon*

*Proceedings of a workshop sponsored by  
U. S. Department of Energy  
Wind Energy Technology Division, and  
NASA Lewis Research Center and held in  
Cleveland, Ohio  
July 28-30, 1981*

**NASA**  
National Aeronautics  
and Space Administration  
Scientific and Technical  
Information Branch

1982



DEDICATION

These Proceedings are dedicated to the Smith-Putnam Project Team,  
sponsored by Beauchamp E. Smith and led by Palmer C. Putnam,  
pioneers in the technology of this Workshop.

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## FOREWORD

The development of large horizontal-axis wind turbines, whose primary use is the powering of electric utility generators, has advanced rapidly in the past five years. In that relatively short time the capacity of experimental wind power plants has been increased by almost two orders of magnitude, from single machines producing 100 kilowatts to a three-unit cluster generating 7.5 megawatts. To document the work of many organizations and individuals who have contributed to this progress and to discuss technical and economic issues, a three-day workshop was conducted by the NASA-Lewis Research Center, under the sponsorship of the U.S. Department of Energy. More than 300 persons met in Cleveland to hear technical papers contributed by manufacturers, government laboratories, electric utilities, and private research organizations.

The technical program of this workshop emphasized recent experience in building and testing large propeller-type wind turbines, expanding upon the proceedings of three previous DOE/NASA workshops at which design and analysis topics were considered (references below). A total of 41 papers were presented on the following subjects:

- \* Current and advanced large wind turbine systems
- \* Rotor blade design and manufacture
- \* Electric utility activities
- \* Research and supporting technology
- \* Meteorological characteristics for design and operation
- \* Wind resource assessments and siting

A highlight of the workshop was the commemoration of the 40th anniversary of the historic Smith-Putnam wind turbine project which produced the world's first megawatt-size wind power plant. Keynote addresses by Messrs. Smith and Putnam are included in these proceedings, together with descriptions of citations presented to them and to members of their project team.

The Workshop Committee is pleased to acknowledge the many contributions of presenters, session chairmen, and staff members which made possible the success of this conference.

### References:

Wind Turbine Structural Dynamics, NASA Conference Publication 2034, DOE Publication CONF-771148, 1978.

Large Wind Turbine Design Characteristics and R&D Requirements, NASA Conference Publication 2106, DOE Publication CONF-7904111, 1979.

Wind Turbine Dynamics, NASA Conference Publication 2185, DOE Publication CONF-810226, 1981.

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LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Keynote Addresses

"Viewpoint in Retrospect"  
Beauchamp E. Smith  
President Emeritus, S. Morgan Smith Company  
York, Pennsylvania

"Wind Power - Yesterday, Today, and Tomorrow"  
Palmer C. Putnam  
Wind Energy Consultant  
Atascadero, California

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## VIEWPOINT IN RETROSPECT

Beauchamp E. Smith  
President Emeritus, S. Morgan Smith Company  
York, Pennsylvania

### INTRODUCTION

I was thrilled to receive an invitation to participate in this DOE/NASA Workshop, just as I was to witness the dedication of the Mod-0 in 1975. Unfortunately, circumstances have prevented me from attending this meeting and hearing the many fine papers being presented in the technical sessions. I deeply regret being unable to join my good friend and colleague, Palmer Putnam, and the others who contributed so much to our project forty years ago.

My disappointment, however, is completely overshadowed by the pride and happiness I feel on this memorable occasion. It is truly an honor at this time of my life to receive special recognition from two of the Nation's most respected organizations: The National Aeronautics and Space Administration and the U.S. Department of Energy.

When Joe Savino asked me to be a featured speaker along with Palmer Putnam, I asked what details I could provide that Put could not describe better. After all, it was Put who conceived and led the entire project. My role was to provide the money and other resources. Joe suggested that I tell this audience why my firm, the S. Morgan Smith Co., had undertaken the project at such a terrible time, in the middle of the great depression, and that I describe some of the benefits we derived from this experience. He convinced me that the Workshop attendees would be interested in the project sponsor's point of view, so I consented to say a few words about how those experiences look in retrospect--40 years later.

### THE VIEW POINT

In 1939 The S. Morgan Smith Company was in the business of manufacturing water turbines and related machinery for the hydroelectric industry. By the late 1930's, most of the desirable sites for hydroelectric plants in the United States had been developed. As a result, the market for our products was declining. To make matters worse, the depression postponed the development of many of those sites which remained.

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There was yet another factor to consider. The S. Morgan Smith Company was a family-owned business that enjoyed the respect and loyalty of its workers. We made every effort to keep our employees working. This was becoming increasingly difficult to do for the reasons I just mentioned. So, in the late 30's, we looked for other areas in which we could utilize our engineering and manufacturing capabilities.

When Palmer Putnam came to us with his concept of using large wind turbines in utility networks as supplemental sources of power, we were interested. There were many small hydroelectric plants in New England and in other sections of the country. Combining them with wind turbines seemed to be an excellent way to boost their capacity. But we were up against some tough competition because the fossil fuels--coal, oil, and natural gas--were very cheap, and seemingly forever abundant. Coal-fired electric power plants were being put up as fast as the demand for electricity increased. The low cost of coal and oil together with the absence of pollution control requirements made the cost of electricity very low. This fact made the development of low-cost wind turbines to compete with fossil fuel plants a real challenge.

Which brings me back to the original question--why did we decide to fund the Putnam project? The answer is simple: It was purely a matter of economic survival that led us to take the chance that this project might lead to a new product line for our company.

Once the commitment was made, we selected Palmer Putnam as the Project Leader, and we proceeded full speed to design, build, and test the 1250-kW machine that became known as the Smith-Putnam Wind Turbine.

I'm not going to discuss our direct experiences with the project in the period from 1939 to 1946. Putnam's book Power from the Wind documents those experiences quite thoroughly. Instead, I'm going to focus on the benefits we realized as a result of our participation in Putnam's concept.

First, we generated work for our company at a time when there was not much work to be had. We were able to keep most of our workers employed until World War II brought about an abrupt surge in demand throughout the economy. Secondly, we received a lot of good publicity. After all, no one had ever built a wind turbine of such a size before. We were the subject of a lot of ridicule too, but the good publicity far outweighed the bad.

The S. Morgan Smith Company also benefited in other ways. Development of new capabilities by our engineering staff was an immediate plus. The fact that this increased capability was noticed by others was evidenced by receipt of contracts to work on projects for which we never before would have considered ourselves qualified.

The long term benefit was an increase in the amount of engineering and manufacturing work our company contracted to perform.

I'd like to give one example--particularly appropriate at this time--of the kind of engineering we were contracted to do as a direct result of our experience with the wind turbine. In the late 40's and early 50's, NASA's Lewis Research Center (then it was known as the NACA Flight Propulsion Laboratory) gave The S. Morgan Smith Company contracts to design, build, install, and put into operation the large air compressors that still power the 10 x 10 and the 8 x 6 supersonic wind tunnels at the Center. I firmly believe my company would never have been asked and would probably never have consented to tackle these jobs if it hadn't been for our experience with the Smith-Putnam Wind Turbine. There are many other examples of projects we were asked to execute because of the added capability we developed meeting the demands of our wind turbine project.

Buried in this account somewhere is the message I wish to impart. We took on a risky project that was beyond our normal engineering experience because we were forced into it by declining economic circumstances. We were very lucky. The risk paid off both immediately and in the long term in ways we had never planned. But as you know, this is not always the case. The message, as I perceive it, is that risks should be undertaken by a private company (and by an individual) when the company is healthy instead of when it is in trouble.

There is a tendency for a healthy company to continue what it is doing as long as the profits are coming in. Private companies in this situation tend not to take on new and different projects. I suggest that the time to strike out in new directions is during a period of strength and profitability. Isn't it possible, for example, that our domestic auto industry would be doing better today if in the period from 1973 to 1980 it had put more of its profits into developing small, reliable, low-cost cars, instead of waiting until people stopped buying the big cars?

Let's apply this message to the wind turbine business; I believe there is a continuing need for a DOE/NASA research program on wind energy. But it is also my belief that now is a good time for private companies to plunge into the development, manufacture, and marketing of these machines. NASA and the Department of Energy have spent a good deal of the taxpayer's money to bring wind turbine technology to the advanced state it is in today. Now is the time for private industry to take this technology, to develop it further and to establish a vital, important, and profitable industry.

By taking this risk, many companies may find themselves far stronger, more diversified, and more profitable. I am told and I have read that there are a few companies that have already gone into the manufacture of wind turbine components, and that they are doing well. That's great and I wish them continued success.

Years ago, I provided some comments that are included in Putnam's book, Power from the Wind. In those comments I expressed the hope that I would live to see the wind turbine market develop. Although it is not yet fully developed, the wind turbine manufacturing industry and the market for these machines is already in the early stages of formation. I am heartened to see this forty-year old dream becoming a reality.

In conclusion, I wish to express my gratitude to the NASA and DOE officials for the honor bestowed on us at this banquet. You have made this occasion one of the most rewarding of my life. In particular, I wish to thank Lou Divone, Ron Thomas and Joe Savino for many personal kindnesses extended to me. Good luck to all of you in your efforts to make the wind one of mankind's major sources of power once again. --

Editor's Note: This speech was delivered on Mr. Smith's behalf by his grandson, Frank C. Zirnkilton, Jr. The S. Morgan Smith Company is now the Hydroturbine, Valve, and Nuclear Division of the Allis-Chalmers Corporation.

## WIND POWER: YESTERDAY, TODAY, AND TOMORROW

Palmer C. Putnam  
Wind Energy Consultant

### INTRODUCTION

Officers of the Department of Energy and the National Aeronautics and Space Administration, citizens of Cleveland, distinguished members of this Workshop, and honored guests. Good evening. I have no words to express how honored and happy I am to be here tonight, sharing in this Workshop with all of you and with my colleagues of 40 years ago, who were referred to by Beauchamp Smith on the telephone last night from Seal Harbor, Maine, as "that motley crew of rugged individualists." What's more, we're all still ambulatory!

Joe Savino has asked me to put together a few thoughts on the theme "Wind Power: Yesterday, Today, and Tomorrow." But, before I make my few remarks, I must say that the kingpin of this occasion is Beauchamp Smith. If it hadn't been for his courage and his vision, we wouldn't be here tonight. But his contribution really goes farther than that. He is the true prophet of windpower, and I have to confess that for many years I was the apostate.

Back in the 50's, I had occasion to visit Beauchamp in his home on other matters, and the conversation came 'round to windpower. He astonished me by saying that he expected to live to see windpower come into its own. I had just finished the last chapter of Power from the Wind, the book that he had asked me to write. In that chapter I had tried to gauge the future of windpower. The best that we could do after five years of experiment was to achieve a design that might possibly generate electricity for about 21 mils per kilowatt hour in a reference wind of 14 miles per hour. But, in New England in those days steam stations were operating at 4 mils. I had found that discouraging and had felt that for a long time windpower would be marginal. It seemed to me that under the best of circumstances wind might possibly carry four percent of the national electrical load at some time in the distant future. So I left Beauchamp's house shaking my head in disbelief, and wondering what he saw on the horizon that I had failed to see.

I realize now some of the dimensions of his wisdom, especially at a time when technology was not evolving at today's pace. Obviously, he had had an intuitive feel for the progress of discovery and invention. If he did not specifically foresee that microprocessors would follow William Shockley's discovery of the transistor, or that OPEC would result from aggressive Arab nationalism, he apparently knew intuitively that there would be some developments which would improve the chances for windpower.

Edgar Allen Poe obviously had Beauchamp Smith in mind when he coined his neat paradox: "Wisdom should reckon on the unforeseen."

So, here we are this evening with 81 units in operation, feeding 13.8 MW into high-lines, and with 2100 other units totalling 500 MW under contract or in negotiation. If the new member of the energy family is not yet a mature adult, at least we can say that the infant is struggling to be born. Beauchamp Smith, witnessing the labor pains from Seal Harbor, has sent us that thoughtful and stirring message that his grandson, Frank Zirnkilton, has just read. I think this is very wonderful and that Beauchamp is due a great tribute for his courage, his vision, and his wisdom.

#### WIND POWER YESTERDAY

Forty-two years ago we had thought there were two questions that had to be answered before we could establish wind as an alternative source of energy.

The first question was, is it possible to convert gusty wind into alternating current so steadily that it will be acceptable to the dispatcher of a utility high-line? This had never been done. No one knew if it could be done. I had kind friends who said it couldn't be done! Second, if it could be done, could the energy be generated at a cost attractive to a utility?

The first major decision we had to make was, what kind of a windmill is the right one to test? Vertical axis or horizontal axis? If vertical, should it be mounted on a track or a pedestal? Should it be Savonius or Darrieus or one of the others? If horizontal, how many blades? One, two, three, or more? Should the generator be aloft or on the ground? Should the drive be mechanical or hydraulic? Should the tower rotate or be stationary? Examples of all of these configurations existed in the literature. Some had been built, but only for the generation of direct current.

Beauchamp Smith and his cousin Burwell reviewed my arguments. They agreed with my parametric selections, namely, the horizontal axis, two-bladed configuration, with a mechanically-driven synchronous generator mounted aloft.

Then came the question: How big shall we make the test unit? Having selected the parameters, I had made two optimization studies with the help of Tom Knight, GE's Vice President for New England. The second study suggested that the optimum size was close to 2 MW, but that the envelope was quite flat in the range of 2 to 3 MW.

At first glance, it seemed sensible to try to get only one answer at a time, and to start out the test with a small unit, say 100 kW. But I was afraid of this. I felt that harnessing gusty winds to produce alternating current smoothly could be so difficult that we might get

a false negative answer from a small unit of low inertia, easily accelerated. I argued that it was essential to make the experiment full scale and that this would have the added advantage of giving us both answers at once. Theodore Von Karman backed me in this, and Beauchamp picked 1250 kW as being the smallest unit representative of the optimum range.

Then came the question of site selection. Being sailors, Tom Knight, Vannevar Bush (then Dean of MIT) and I knew that the roaring forties were windy, with strong westerly components. New England lay in the forties. The Green Mountains of Vermont trended north-south. Without discussion, it was tacit among us that the test site should lie somewhere in the Green Mountains.

But specific site selection was quite another matter. In our innocence, we thought we could look at the profile of a ridge and say: "This ridge obviously will accelerate the free air flow while that one won't." Thus, we guessed that Grandpa's Knob would accelerate the free-air wind by a factor of 1.2. After five years of observation we concluded Grandpa's had actually retarded the free-air flow, giving us a factor of 0.9.

Also, in our innocence, we thought that if we tested models of candidate sites in the wind tunnel, we could obtain precise information about the wind velocity over a ridge. Even while proceeding with the selection of Grandpa's Knob, we made four models of other Green Mountain sites. Over 20,000 measurements were taken in the Guggenheim wind tunnel at Akron with inexhaustible ingenuity, under the supervision of Von Karman. Our regretful conclusion, since confirmed in England by Golding, was that model testing of wind sites yields no useful information.

We tried every other method we could think of to evaluate quickly what appeared to be the more attractive sites in New England. Dr. Karl Lange of Harvard, for example, flew balloons in westerly winds over a number of the sites, following their trajectories with range-finders. Because of turbulence, the method proved useless.

In the end, the tool that we discovered to be most useful, short of actual anemometry, was what I called "quantitative ecology," which I worked out with the botanist, Dr. Robert Griggs. He and I discovered that the deformations of evergreens by wind, which are easily observed and which fall into half a dozen readily identifiable categories, were good wind prospector's tools. We found it possible to look at deformed evergreens and say: "At this site the long-term mean annual velocity at a hub height of 140 feet will be 25 miles per hour, with a probable error of about 10 percent." However, until we had taught ourselves this new technique, our only recourse was anemometry, and the constraint of the impending war forced us to select a site for the test unit without waiting for such measurements.

Map and field studies had suggested to Hurd Willet that the four-mile-long Lincoln Ridge should be a powerful site. But it stood at 4,100 feet, and we were all afraid of icing. It seemed to me that the experiment was going to be chancy enough, without the challenge of ice. So I chickened out and joined the opposition to Lincoln Ridge. Now we know that ice is no problem.

We sailors thought that our educated guesses of the output at the 2000-ft. Grandpa's Knob were sufficiently reliable to permit the experiment to proceed. In the end, we obtained only thirty percent of the output we had predicted. So much for the intuitions of sailors about specific site selection!

The next major decision was, how to make the blades and of what? We had several delightful discussions with Frank Caldwell, Chief Engineer of Hamilton Standard Propeller, but he decided that a propeller 175 feet in diameter was too much for the then state of his art.

The Budd Company had been making stainless steel trains and destroyer superstructures under Dick Heckscher, who volunteered to break new ground and make up our blades out of stainless, to the aerodynamic specifications of Von Karman and Homer Joe Stewart.

In 1939 the phony war was already on. Our own eventual entry seemed likely, and American industry was already gearing up for war production. We felt that if we did not order the long lead time items promptly, we might not get them for many years to come. For this reason, the entire project was driven at a fairly fast clip under Bud Wilbur as Chief Engineer, with the assistance of Chris Holley. By the way, Chris said to my wife yesterday that he's been going around this conference feeling like Orville Wright.

The Smiths made the decision to proceed with the project in October 1939. Seventeen months later, Stan Dornbirer had erected the unit, despite a Vermont winter. After some months at slow rotation, followed by more months at speed-no-load, Bill Bagley of GE, on the evening of 19 October 1941, phased the unit into the lines of the Central Vermont Public Service Corporation in a northeast wind gusting to 25 mph.

Within half an hour, while generating 500 kW, we got the answer to our first question. We could indeed make gusty winds generate alternating current smoothly enough to be acceptable to the dispatcher of the high line. In fact, the operation was so smooth that Ralph Durgin, the Chief Engineer of Central Vermont Public Service Corporation, told me later that they took their regulation from Grandpa's Knob rather than vice-versa!

Thereafter the unit was operated for several hundred hours under Grant Voaden's test program until one of the 24-inch main bearings failed. The failure had nothing to do with windpower in general, or

with the design of our unit specifically. But, because it occurred during the war, it took many months to replace. The unit was then started up again and in all had logged about 1,100 hours of very smooth operation when we lost a blade.

Many years later I was consoled for the blade loss by Clyde Jones, who had been Howard Hughes' Chief Engineer in the design of the Hughes helicopters. He told me that if we hadn't lost the blade then, we would have been bound to lose it later, because in those days nobody knew anything about the stress analysis or the fatigue factors of helicopter rotor hubs. They didn't become reliable until the mid'fifties.

When I consider the elegant computerized structural stress analyses that today have permitted Hamilton Standard and Boeing and GE and Westinghouse, for example, to reduce or balance out stresses, thus reducing weight with confidence, I am somewhat appalled at the blythe temerity with which we attempted to design our hub in those days. If I had known then what I have learned since, I would hardly have dared recommend the project to Beauchamp Smith.

After the war, in the light of five years' experience and of suggestions from many of the members of the team who are here tonight, two further sets of optimization studies were carried out under the direction of Carl Wilcox, working in the offices of the Budd Company. The final set confirmed the three previous studies and indicated that the optimum capacity would lie somewhere in a range between 1.5 and 3.0 megawatts, but with an envelope that was quite flat at the higher capacities.

Assuming a production run of 100 units, the lowest conceivable capital cost in 1945 was a very uncertain \$100 a kilowatt. Installed on Lincoln Ridge, where the velocity at hub height was 27 miles an hour, this would have meant a cost of electricity at the bus of about 5.3 mils a kilowatt hour. But in New England then, as I mentioned, utilities could not afford to pay more than 4 mils for wind energy.

So, we had our two answers. Yes, we could convert gusty wind energy into alternating current smoothly enough for the dispatcher of a high-line. No, we could not do so economically.

Beauchamp asked me to write Power from the Wind. And we all then turned to other things.

#### WIND POWER TODAY

If NASA's predecessor had held a workshop on windpower 40 years ago, the Smith-Putnam Team would have been the only attendants. But there would have been no papers because nobody knew how to write them.



Here we are today attending this workshop, so beautifully organized by Dave Spera and Joe Savino of NASA and Bob Thresher of Oregon State. We've now spent two stimulating days discussing 23 papers concerning the specifics of windpower today. I'll make no attempt to summarize all this. Instead I'll try to look at windpower in the large, with the fresh eye of someone who has just returned to it after a long absence.

It's a matter of great satisfaction and some astonishment to observe that my parametric selections of 40 years ago have stood up. DOE and NASA have funded parametric studies by GE, Boeing, and others, using computers. These studies have confirmed my parametric selections (Fig. 1). Even the computerized optimization studies gave results that were not dissimilar to ours of 1939 and 1945. The envelope of the capacity curves is still flat, although the minimum point is further to the right.

As we all know, the most recent optimization studies by GE, Boeing, and Hamilton Standard suggest that the optimum capacity today lies somewhere in the range of 5-7 megawatts (Fig. 1). It has been explained to me that this shifting of the minimum point of the envelope to the right has not been the result of fundamental design changes. It has been in improvements in the past ten years in computerized structural analysis solidly based on a billion flight hours of helicopter experience, and backed up by such inspection techniques as sonic and X-ray examinations. The net result of all of this has been an ability to greatly reduce the weight per kW.

For example, as shown in Figure 2, our Grandpa's Knob machine weighed 598 pounds per kW. Our pre-production design of 1945 brought this weight down significantly, to 470 pounds per kW. But, GE's Mod-5A is now reported at 184, Boeing's Mod-5B at 179, and the others are also under 200 pounds per kW. This paring away of 2/3 of the unit weight is what has permitted a tripling of the optimum capacity, from a little over 2 MW to a little over 7. I've also been told that about 7.2 MW, with its associated diameter of 500 feet, is perhaps an absolute limit today. It's as high as we can go with available bearings.

In 1945, when steel railroad gondolas were selling for 6 cents a pound, our preproduction unit cost 31 cents F.O.B.--a ratio of 5 to 1. In 1981 gondolas are priced at 59 cents a pound, while the 100th unit of GE's Mod-5A is quoted at "less than" \$2.95 a pound--also a ratio of 5 to 1. At the other end of the size spectrum, the 25-kW Carter unit is priced at about \$4.00 a pound F.O.B.

These ratios suggest that not many manufacturers of intermediate and large wind turbines will be tempted to offer their machines at much over \$4.00 a pound, in 1981 money.

In the final sentence of Power from the Wind, I had said in 1945 that it would probably take government help to get low-cost production runs started. Since the oil embargo of 1973, DOE has spent a quarter of a billion dollars to stimulate windpower. Apart from the splendid Battelle 12-volume atlas of the Nation's wind resource, and innumerable studies by such groups as JBF Scientific; Booz, Allen and Hamilton; Arthur D. Little; EPRI; SERI; and others, the bulk of the money has gone to fund the production of hardware, looking to the evolution of a commercial multi-megawatt production unit.

Beginning with NASA's 100-kW Mod-0 at Plum Brook in 1975, continuing through the Westinghouse 200-kW Mod-0A series at Clayton, Block Island, Culebra and Kahuku Point on Oahu, through GE's 2.5-MW Mod-1 at Boone, and Boeing's three 2.5-MW Mod-2's for Bonneville Power, we have just now arrived at the design studies of the first units of the fourth generation. It is hoped that their tests will show them to be mature prototypes, and the basis for production designs. They are the Mod-5's of Boeing and GE, rated up to 7-MW, and the 500-kW of Westinghouse. Also, in the private sector, there is the WTS-4 of Hamilton Standard, rated at 4.8 MW. I am told the first unit of this design should be on line in Sweden in November. And the first WTG 500-kW is in the wings.

In short, the birth of the baby is underway. At this interesting juncture, the administration has been saying that it must turn out the hospital lights and send the staff home, leaving the baby to be weaned while delivery is underway. Can there be a live birth without further help? I don't know. It remains to be seen whether the private sector will take up the slack. In the meantime, what can we say about the infant, from as much as we can see of it? Is it a healthy specimen?

We still have the same two questions that faced us in 1939, but in the reverse order. As I will try to show in the next section, "Windpower Tomorrow", however shaky the transition economics may appear, the ultimate economics are no longer in doubt. It is now the technology as perceived by venture capitalists, whose maturity is in question.

Recently I was talking with the chairman of one of the Fortune 500. He summed up his view of windpower by telling me that windmills either blow down or blow up, or, if they work, they are noisy: To hell with them!

Regrettably, the test record does contain just such episodes, but I seem to remember that some early airplanes failed and some early helicopters did shed blades. If wind turbines appear to have had a very large number of accidental shutdowns, I wonder if this hasn't been due in part to a very general impression that harnessing the wind is child's play? Didn't we have millions of windmills pumping water in the last century? Weren't they reliable work horses, year-in, year-out, often with service lives of fifty years or more? All true, but deceptively irrelevant.

The truth is, harnessing the wind to generate alternating current is a straightforward enough problem, but more subtle and difficult, apparently, than many people have realized. Wishing to develop renewables, people have said to themselves, "Hey, let's build some windmills." And they have. And the windmills have blown down or blown up or gone thump in the night.

I believe that in the multi-megawatt range, the Mod-5 design concepts of GE's Dan DiGiovacchino, of Boeing's John Lowe, and the WTS-4 of Hamilton Standard's Art Jackson, are very promising preproduction prototypes.

I believe this to be true also of the intermediate 500-kW unit of Will Treese of Westinghouse and of the 125-kW unit of Carter of Texas. I wonder how many in this audience would disagree?

Finally, among the small machines, there is the interesting case of the 50 kW unit of U.S. Windpower, assembled from stock components (apart from the blades), and going into a 100-unit windfarm by year end.

Some of these designs are truly elegant in their simplicities, and their predecessors have already shown reliabilities of 85 percent. Their electronic redundancies are protected by inherently fail-safe mechanical redundancy against over-speed.

So the practical questions today are two: How do we bridge the remaining tantalizingly short R&D gap before production can begin? How can a manufacturer get to his competitively priced 100th unit?

Which brings us to the crystal ball.

#### WINDPOWER TOMORROW

Is there anything useful that can be said about the future of windpower? Every time I hear something by a futurist, I think of what that Anglo-French philosopher Hilaire Belloc once said: "Men prophesy and the future makes fools of them."

About all one can do, it seems to me, is to identify some of the trends likely to help or hinder windpower.

What about the future trend in the cost of wind-generated energy at the bus?

According to the statements of the manufacturers, 1981 costs of energy at the bus, in the 14-mile reference wind, generated by machines that could become available in 2 to 4 years, are asymptotic to about 2.5 cents a kWh (Fig. 1).

Is any breakthrough in sight, that would dramatically reduce these costs?

As we have heard, there are people who are wondering if variable speed might be cost effective. Others are studying the possible elimination of hydraulics, and so on. Even if effective, these steps would be only refinements. No quantum jump is on the horizon.

Are no quantum jumps conceivable?

Everybody knows that negative statements are often disastrous. Wasn't it the great physicist, Lord Kelvin, who, as president of the Royal Society, said that heavier-than-air flight was impossible? And wasn't it Ernest Rutherford, the discoverer of the atomic nucleus, who said that the energy in the atom could never be released?

Recently I've been trying to touch most of the bases in our small world of windpower, by visits, by telephone and by reading. As your friendly neighborhood reporter, I can only say that I've encountered no whisper of what a breakthrough might look like.

As of today the logo of this splendid conference appears to say it all. In 1939 the multi-megawatt way to go was the two-bladed horizontal-axis machine. In 1981 it's still the multi-megawatt way to go.

With no breakthroughs in sight, let us then examine the extent of the market for wind energy in the light of what we know today about the demand for it and about the costs of its competition, that is, the costs of coal, natural gas and oil.

The portion of the market that is most often talked of consists of blocks of windpower in the form of windfarms, added directly to a utility's generating mix.

How large is this market? Total generating capacity in the U.S. today is about 600,000 MW. By the end of this century, it may increase by 200,000 MW. Could wind supply fifteen percent of this increase, which would be about 30,000 MW, or about four percent of the total? Such a penetration does not seem implausible. This market would absorb mostly the large and intermediate machines.

What are the economics of this market? To start with, what are the trends in the cost of wind energy at the bus in constant 1981 dollars, and in the 14-mile reference wind? Figure 3 illustrates possible cost trends. In 1945 our hypothetical cost of energy at the bus, in 1981 dollars, was about 126 mils per kWh. If today we take various manufacturers' claims at face value, then the COE in constant 1981 dollars will have dropped about 76 percent, to about 30 mils or less by about 1984. Refinements will surely continue to reduce the

COE in constant dollars, perhaps reaching about 27 mils in 1990 and 24 mils in 2000. By contrast, a specific utility, when peaking with natural gas in 1981, has a COE of 65 mils. But this apparently comfortable margin is not the whole picture.

The U.S. utility industry is having a hard time financing conventional additions to plants. Even if it wished to, a utility would be unlikely to obtain a P.U.C. permit to add an unproven source of energy to its rate base.

At least in its introductory years, therefore, large-scale windpower that is a part of utility's generating mix would require third-party financing. While long-term Treasuries are earning 14 percent, with minimum risk, and until wind technology becomes mature, venture capitalists are going to demand a minimum of 35 percent internal rate of return on their investment. This means that a windfarm generating for three cents at the bus must then add the costs of the venture capital, amounting to several cents more, to arrive at a selling price possibly falling in the range of 5 to 8 cents. (Three windfarms are now venture-capital financed. Rolf Laessig described two of these this afternoon.)

How does this range in the selling price compare with the worth of wind energy to a utility? The principle worth is as a substitute for coal, gas or oil. What can we say about the trends to expect in the costs of these fossil fuels?

Let's look first at crude oil prices. Whether they are trending up or down depends on the expert you consult. A couple of weeks ago a New Jersey think-tank saw crude's prices tumbling down from \$40 a barrel to \$20 and \$10 or less. The argument went like this: Without altering our life-styles very much we have decreased our imports in the last 3 years from 8 million barrels a day to 5. Others can and will continue this process. Non-OPEC production is rising. The conclusion: OPEC has lost its leverage.

But, if you don't care for this scenario, then turn to the Wall Street Journal of a week later. The glut is over. Inventories have been pared down. World demand is increasing. Prices are firming and will go on up.

Fortunately for windpower, and except in special cases, it may not be very important in a general way which scenario proves correct, because the national fuel mix for generating electricity contains only 15 percent oil. One special case of great importance, however, is the West Coast and Hawaii, where utilities are heavily dependent on oil. If oil prices should fall, windpower there would face a very tough challenge.

Apart from nuclear, most generation is by coal. What about the future trend in the price of coal? Those who follow the fortunes of coal estimate that its price may conform to the trend in the inflation rate, within a few percentage points either way.

If the price of coal, especially of sub-bituminous coal, should not escalate at the general inflation rate, then it might be nearly a decade before wind could generate more cheaply, except at the windiest locations. This time-frame does not allow for the monies that wind must earn to reward the venture capitalists.

When natural gas is deregulated, a portion of that fuel may increase in price five times or more. The average price may go up 50 percent, and the Congress, with administration backing, has now rescinded the law that deprived utilities of all natural gas by the year 2000. On balance, therefore, the future of gas prices should help windpower in those localities where utilities burn this fuel (Fig. 3).

Those utilities burning mostly coal and gas have base-load costs of about three cents and peaking costs of perhaps twice as much, or more in some cases. Most of them should be able to pay somewhere between these limits for wind energy. If a levelizing factor of 2 is acceptable, then perhaps several cents more. For preliminary planning we might think of a range, therefore, between levelized base-load costs of about 6 cents and levelized peaking costs of perhaps 10 to 12 cents, yielding a margin that ranges from nothing in some cases to as much as 4 to 5 cents in the most favorable cases.

If aspects of this market seem a bit tight, we may reflect on four additional factors. First, interest rates of 14 percent for long-term Treasury notes are not likely to be permanent. Second, I've been talking averages, but there are some special cases, not only in the continental U. S., but also in the Caribbean, on some oceanic islands, and, perhaps, in certain foreign countries. Third, although it varies from utility to utility, in certain specific cases it will be found that wind can earn a capacity credit. Fourth, windpower almost always earns a KVA or power-factor credit of at least a few dollars a kW.

The costs of venture capital are soon to be a heavy burden in this utility market. Is there any way to avoid the cost of this venture capital assistance? Yes, there is. By selling directly to businesses, institutions and individual ranchers and farmers, who will then harness the wind for their own account, selling the excess to the utility through a two-way meter. Price relief appears at both ends. First, the avoided costs of the individual user are what that user is now paying the utility. These costs may run from 5 to 12 cents or more. Second, the cost of the wind-generated energy will drop by the amount that the venture capital would have cost. As we have seen, that amounts to several cents.

The sum of these two reliefs may amount to 4 to 8 cents or more, creating a total margin that might run from a few cents to 10 or even more in certain special cases. Of course, a part of this larger margin will be needed to defray the extra costs of researching and penetrating this more diffuse market.

How large is this private market? I can't find any close estimates. There are suggestions that it may amount to another 10,000 MW by the end of the century, suitable for the smaller and intermediate size machines.

I've said nothing about government assistance. Just as the airlines needed government subsidies at first but are now on their own, so windpower, having had the government help I asked for 35 years ago, must look forward to ultimate prosperity without help. Has that time arrived? Surely not quite yet. We are in transition barely.

In sum, then, what are the salient points about windpower that offer some clues to its future? I think there are four.

1. Design

The essential design parameters haven't changed in 40 years. There is nothing in sight to suggest a revolutionary breakthrough. The costs of wind energy in constant dollars have declined 76 percent in 36 years. They may decline a few percentage points further, but a revolutionary decline is not foreseen.

2. Reliability

Today there are already machines that run silently with a reliability of over 85 percent. Higher reliabilities should result from the orderly development of quality control in production.

3. Economics and the Market

- A. The domestic market for windpower may amount to 30,000 MW by the end of the century, with costs at the bus between 2 and 3 cents in 1981 dollars (Fig. 3). The foreign market is not yet measured. Wind energy financed by venture capital must receive a minimum of 5 to 8 cents a kWh to be profitable.

- B. An additional market consists of direct sales to businesses and individuals, without venture capital. The domestic private market may amount to 10,000 MW by 2000.

#### 4. Government Help

In the multi-megawatt range, public R&D has developed the Mod-5 designs and concepts of Boeing and GE. There remains, however, a 3 to 4 year test program before production. If this minimum remaining public assistance is not forthcoming, large-scale windpower could suffer a set-back and long delay. Even if manufacturers do start production, windpower in general may still need tax relief for perhaps a decade before it can stand alone.

I heartily endorse Belloc's remark about prophecies. I wouldn't ask 10 seconds of your time to listen to a prophecy. But I don't think a dream is in the same category as a prophecy, is it? I do have a dream I'd like to share with you. I dream of a galaxy of windfarms--many thousands of megawatts--deployed in the mid-continent region and along the foothills of the Rockies, in reference winds of 16 to 19 miles an hour, all tied together by upgraded high-lines and feeding into the great power pools and grids of the region; these blocks of power to be amplified by multitudes of units sold directly to private users without the need for venture capital.

My dream has brought me a new partner, Aerovironment. I've mentioned that Theodore Von Karman had been our senior scientific advisor and chief aerodynamicist. He was assisted in this by his ablest graduate student, Homer Joe Stewart, who is here tonight. Stewart, succeeding Von Karman at Cal Tech, had an able graduate student in his turn, the amiable Peter Lissaman, Vice President of the Aero Sciences Division of Aerovironment. As most of you know better than I, it was Lissaman's work that has been so fundamental to the design of modern wind turbines and the geometry of windfarm arrays.

I'm so happy to be the beneficiary of this apostolic succession--Von Karman to Stewart to Lissaman. The President of Aerovironment, another student of Homer Joe Stewart, is Paul MacCready, of Gossamer Condor fame, whose Solar Challenger has just flown from France to England. Last year he and Von Karman were each named by the ASME "Engineer of the Century." With such associates, I dare to hope that you'll be hearing more about my dream - soon.

I'm not overlooking environmental resistance. I am an environmentalist. I have to believe that most people want windpower to succeed. A few weeks ago I was in Clayton, N. M., to study Westinghouse's 200-kW Mod-OA, which I found putting out 150 kW in 25 mph of gusty southwest winds. I asked Eli Garcia, the City Manager, if the townspeople were opposed to the unit. He told me that, on the contrary, they were proud of it and proud to be using the wind. We stood beside a house about 800 feet downwind. The unit could not be heard above the rustling of the leaves in the trees!



May I close by quoting the last paragraph of my foreward to the new edition of Power from the Wind, which has been updated by Professor Jerry Koeppel, and is to appear in September. It was written before my visit to Clayton.

"A seascape or a landscape without a work of man in the middle distance is often thought to be not worth photographing or painting. An expanse of mere ocean does not say much. Put a laboring vessel in the middle distance, and there is a point of interest - dramatic value. A distant mountain range is just there. Add a forest ranger's tower: the composition begins to say something. How much more will it say when a slender tower is seen to support two blades that rotate slowly, gracefully, silently - evidence that man is once again, and at last, using his environment benignly!"

Thank you very much.

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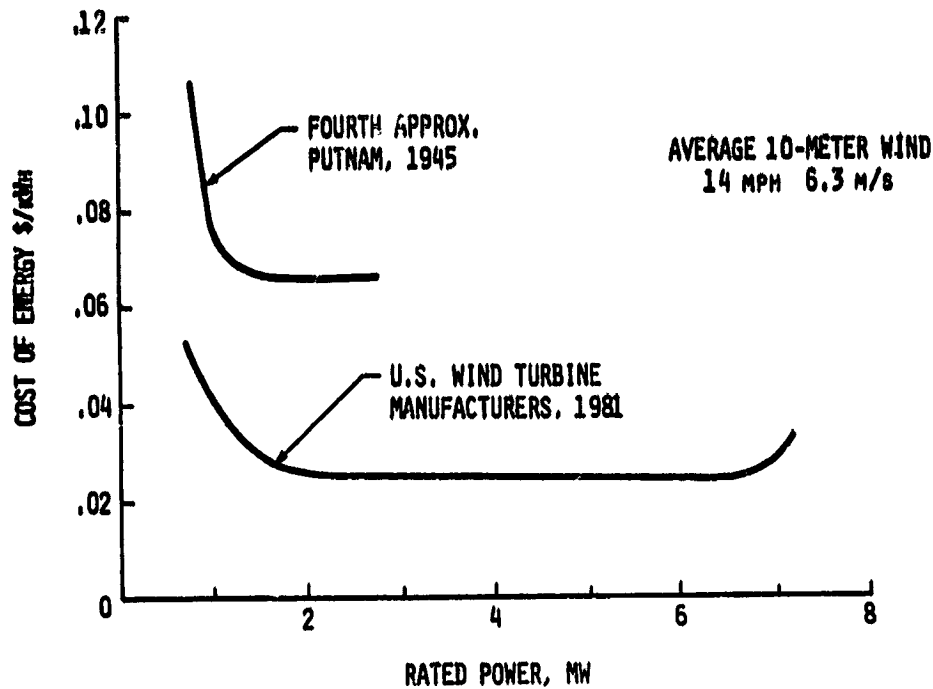


Figure 1. - Effect of turbine size on energy cost

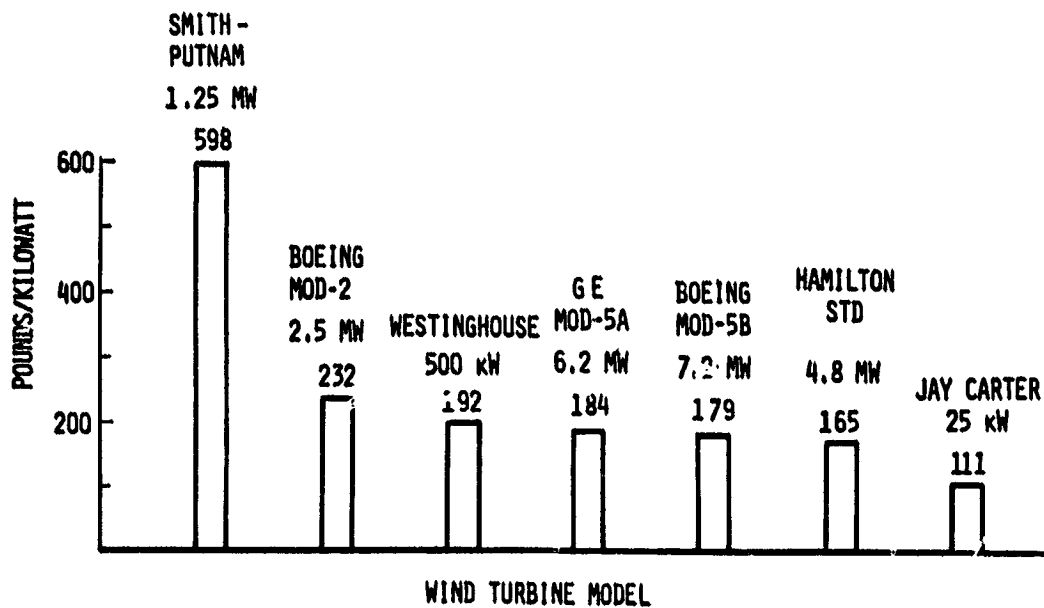


Figure 2. - Weight-to-power ratio of various wind turbines (weight above foundation and rated power).

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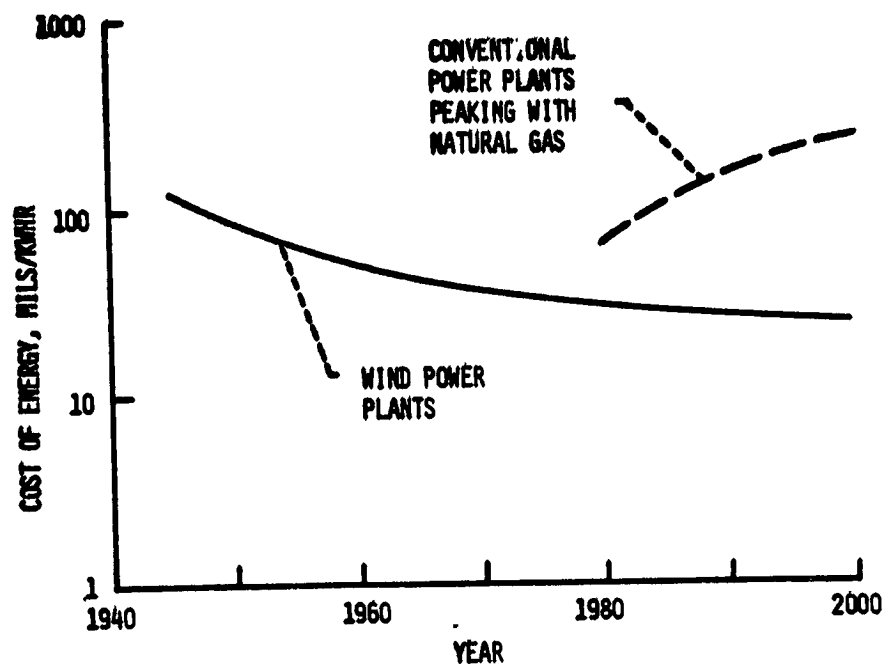


Figure 3. - Possible trends in the cost of energy generated by wind power, compared with conventional plans using natural gas as fuel (constant 1981 dollars; busbar costs).

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LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Ceremonies Commemorating the Fortieth Anniversary of the Smith-Putnam Wind Turbine Project

Awards to the Smith-Putnam Project Team

Beauchamp E. Smith  
Palmer C. Putnam  
Dr. John B. Wilbur  
Grant H. Voaden  
Carl J. Wilcox  
S. nton D. Dornbirer  
Dr. Homer J. Stewart  
Myle J. Holley, Jr.  
Dr. Hurd C. Willett  
Wellman Engineering Company

"The Smith-Putnam Wind Turbine"

Grant H. Voaden

Reprinted from Turbine Topics, Volume 1, No. 3, June 1943

A Publication of the S. Morgan Smith Company

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FORTIETH ANNIVERSARY AWARDS TO THE SMITH-PUTNAM PROJECT TEAM

This Workshop provided an excellent opportunity for the wind energy community to honor Beauchamp E. Smith, Palmer C. Putnam, and key members of their project team for pioneering achievements in wind power development. Forty years ago, this team designed, built, and operated the world's first megawatt-size wind power plant. On October 19, 1941, the Smith-Putnam 1250-kW wind turbine (below) was brought on-line as a generating station of the Vermont Public Service Corporation. The historic Smith-Putnam project advanced the field of wind power engineering from small DC generators and water pumpers to large AC units capable of integration into electrical supply systems.

To honor these achievements, citations were awarded by NASA, in cooperation with the U.S. Department of Energy, to Messrs. Smith and Putnam, and to the following eight members of their project team: Dr. John B. Wilbur, Chief Engineer; Grant H. Voaden, Assistant Chief Engineer; Carl J. Wilcox, Administrative and Project Engineer; Stanton D. Dornbirer, Manager of Assembly and Operations; Dr. Homer J. Stewart, Aerodynamicist; Myle J. Holley, Jr., Structural Analyst and Designer; Dr. Hurd C. Willett, Meteorologist; and the Wellman Engineering Company of Cleveland, Principal Designer and Manufacturer.

The following pages contain brief descriptions of the award recipients and their roles on the project team.



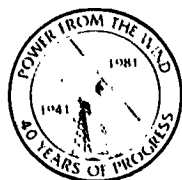
The Smith-Putnam 1250-kW Wind Turbine  
1941-1945

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Beauchamp E. Smith  
1901 — 1981



National Aeronautics and  
Space Administration

Lewis Research Center

*in cooperation with*

Department of Energy

*Honors*

**Beauchamp E. Smith**

*a pioneer in the development of large Wind Turbines  
as a source of clean renewable energy for his  
leadership, courage, and fore-sight which made possible  
the construction and operation of the  
World's First Megawatt-Size Wind Turbine  
at Rutland, Vermont, from 1941 to 1945.*

Cleveland, Ohio

July 29, 1981



## Beauchamp E. Smith

### Project Sponsor

Beauchamp E. Smith was born in York, Pennsylvania, on October 8, 1901. He attended Haverford School and graduated from Cornell University with a Degree in Mechanical Engineering. During 1924 and 1925 he was employed by the Georgia Power Company, first as a draftsman and later as a field engineer. He joined the S. Morgan Smith Company as a junior engineer on December 1, 1925. From 1927 to 1937 he served as secretary and director of the company. He became vice president and general manager in 1937 and president in 1942.

When the S. Morgan Smith Company was acquired by Allis-Chalmers Manufacturing Company in 1959, Mr. Smith became a vice president of Allis-Chalmers and the general manager of the corporation's Hydraulics Division. After his retirement in 1961 he served as a director of the Allis-Chalmers Corporation until 1974.

It was during his tenure as vice president and general manager of the S. Morgan Smith Company that Beauchamp Smith's belief in the feasibility of wind power was put into action. He persuaded the company directors to sponsor Palmer Putnam's unprecedented wind power project. Under his guidance, the company constructed a megawatt-size wind turbine generator in 1941--the first in history.

Speaking at the 1975 dedication of the NSF/NASA Mod-0 wind turbine, Mr. Smith said "I always felt that something good would come out of our tests in the 1940's, even though we were ridiculed at the time. Energy sources seemed then to be more abundant than our country would ever need. We were just ahead of our time. I got a great feeling of satisfaction today when I saw those majestic blades going around."

Beauchamp Smith was always active in the leadership of educational, charitable, commercial, and professional organizations. He served on many boards of directors and trustees, including those of the Massachusetts Institute of Technology, the National Electrical Manufacturers Association, and the Cornell Engineering College Council.

Because of illness, Mr. Smith was unable to attend the Workshop. His citation was accepted for him by his grandson, Frank C. Zirnkilton, Jr. On September 21, 1981, shortly after the Workshop, Beauchamp Smith died at his summer home in Seal Harbor, Maine.

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Palmer C. Putnam



National Aeronautics and  
Space Administration  
Lewis Research Center

*in cooperation with*  
Department of Energy

*Honors*

**Palmer C. Putnam**

*a pioneer in the development of large Wind Turbines  
as a source of clean, renewable energy and  
who conceived and led the construction and operation of the  
WORLD'S FIRST MEGAWATT- SIZE WIND TURBINE  
at Rutland, Vermont, from 1941 to 1945.*

Cleveland, Ohio  
July 29, 1981





## Palmer C. Putnam

### Project Originator and Leader

Palmer C. Putnam is one of those creative persons of immense energy who cannot be easily classified--his accomplishments are so many and so varied. During World War II, he worked as a special assistant to the director of the Office of Scientific Research and Development, Vannevar Bush. In that position he invented 10 original weapons and directed the development of 22 others. Among them was the well-known amphibian vehicle, the DUKW, which the German General von Rundstedt called "a strategic surprise that assured the success of the Allied invasion of Normandy." Mr. Putnam received the Medal of Merit from President Franklin D. Roosevelt for his contributions to the war effort. The citation accompanying the medal stated that "his efforts undoubtedly resulted in shortening the war and in saving the lives of many American and Allied soldiers."

Mr. Putnam operated his own business and was the president and board chairman of G.P. Putnam & Sons, one of the oldest publishing firms in the country. He has been a consultant on projects too numerous to list here. He is the author of several books, one of them the renowned Power from the Wind. It is not surprising, therefore, that it was Mr. Putnam who conceived and led one of history's most successful attempts to harness the wind on a large scale.

Mr. Putnam's interest in wind power was stimulated in 1934 when he noticed that both the winds and the cost of electricity were high on Cape Cod where he had built a summer home. These two facts prompted him to investigate, with the help of many prominent engineers, the feasibility of generating electricity from the wind. His investigation eventually led to the design of the 1250-kW unit that was built and installed on Grandpa's Knob in 1941 under the sponsorship of the S. Morgan Smith Company of York, Pennsylvania.

By his foresight, creativity, and leadership, Mr. Putnam demonstrated that large wind turbines can be integrated into utility networks as a supplemental source of clean, renewable power. Had today's energy shortages existed forty years ago, there is no doubt that Mr. Putnam's machine would have been followed by thousands of large wind turbines in operation around the country and the world.

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**Dr. John B. Wilbur**  
**Chief Engineer**

As Chief Engineer of the Smith-Putnam project, Dr. Wilbur coordinated all of the design, fabrication, construction, and testing activities from 1939 to 1945. As he recalled at the Workshop, "The design was being carried out by experts all across the country, from MIT to Cal Tech, from the Budd Company in Philadelphia to American Bridge in Pittsburgh to Wellman Engineering in Cleveland. These were very creative people. My job was to focus all this creativity on one project."

Dr. Wilbur's distinguished career has encompassed a broad range of positions and experience. In 1930 he joined the faculty of the Civil Engineering Department at Massachusetts Institute of Technology. He rose to the rank of full professor and became department head. He is a Fellow of the American Society of Civil Engineers, serving as the president of its Northwest Section. Dr. Wilbur is also a Fellow of the American Academy of Arts and Sciences. In 1947 he received the highest award given by the Boston Society of Civil Engineers for a paper he wrote about the Smith-Putnam wind turbine. Since 1970 he has been Professor Emeritus at MIT and is enjoying life these days in Hancock, New Hampshire.



**Grant H. Voaden**  
**Assistant Chief Engineer**

Mr. Voaden was employed by the S. Morgan Smith Company from 1925 until 1968. In 1939 he was assigned to work full-time on the Smith-Putnam wind turbine as the Chief Test Engineer, reporting to Dr. John B. Wilbur. Mr. Voaden later became Assistant Chief Engineer. In the early stages of the project, he was involved in the design of the machine and in the selection, coordination, and purchase of the hydraulic and electrical control equipment. He also helped with the assembly on Grandpa's Knob, trained the wind turbine operators, and managed the field-test program.

Since 1968, Mr. Voaden has been enjoying retirement in York, Pennsylvania.

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**Carl J. Wilcox**  
**Administrative and Project Engineer**

Mr. Wilcox worked on the wind turbine project starting in early 1940, when he was employed by the Budd Company which built the blades. There he participated in design of the rotor blades, analyzed aerodynamic performance, and conducted some of the first economic studies for large wind turbines. In June 1941 he joined the S. Morgan Smith Company as administrative engineer in charge of the company's Rutland, Vermont office. In this position Mr. Wilcox monitored operations at the test site on Grandpa's Knob, 18 miles away, collected and processed test data, and wrote many of the reports on the Smith-Putnam project. He was also involved in the economic assessment studies which were made for the company after the blade failure in 1945.

From January 1946 to April 1947, Mr. Wilcox assisted Palmer Putnam in the preparation of his book Power from the Wind which has achieved world-wide recognition. From 1947 until his retirement in 1976, he held a number of important management positions at the S. Morgan Smith Company. He continues to live in York, Pennsylvania, his home of 40 years. With his fund of information on the wind turbine and the people who designed and built it, Carl Wilcox is the unofficial historian of the Smith-Putnam project.



**Stanton D. Dornbirer**  
**Manager of Assembly and Operations**

Most of Mr. Dornbirer's professional career was spent with the S. Morgan Smith Company from the 1930's until his retirement in 1963. He managed the field installation of heavy machinery and equipment across the United States and abroad. In 1940 he was assigned to the wind turbine project, with responsibility for the entire assembly operation, including shop assemblies in Cleveland, Pittsburgh, and Philadelphia, and field assembly on Grandpa's Knob. In spite of bitter winter weather, absence of roads, and an almost impossible schedule, Stan Dornbirer fulfilled his responsibility. After the machine was assembled and in operation, his task was to keep it running and to supervise maintenance and repair work.

Mr. Dornbirer is a native of Cleveland, where he graduated from the Case School of Applied Sciences (now Case-Western Reserve University). Among his many engineering accomplishments are the construction and installation of the huge compressors in two supersonic wind tunnels at the NASA Lewis Research Center in Cleveland. During the Workshop, he inspected these compressors, obviously pleased with their performance during the past 30 years. Mr. Dornbirer is still active as a consulting engineer based in Inglis, Florida, his retirement home.

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**Dr. Homer J. Stewart**  
**Aerodynamicist**

Dr. Stewart's contribution to the Smith-Putnam project was the development of the unique design of the rotor blades. As a graduate student at the California Institute of Technology, he worked closely with Dr. Theodore von Kármán to select an airfoil shape that was both efficient and economical to build. They evaluated many designs, both by theoretical analysis and by wind tunnel testing. Dr. Stewart's studies led to the selection of constant-chord blades each individually hinged to relieve loads. This research on rotor aerodynamics produced some of the most significant contributions which were made by the Smith-Putnam project team.

Dr. Stewart is Professor Emeritus of Aeronautics at the California Institute of Technology. During his long and distinguished career he has made many pioneering contributions to the development of modern rocket engines. In 1958 and 1959 he helped usher in the Space Age as NASA's first director of the Office of Program Planning and Evaluation. Dr. Stewart and his wife Frieda presently reside in Altadena, California.



**Myle J. Holley, Jr.**  
**Structural Analyst and Designer**

Mr. Holley became a member of the Smith-Putnam team in September 1939, while still a graduate student at the Massachusetts Institute of Technology. One of his first responsibilities was to analyze dynamic loads and stresses in critical components, an effort which was largely without precedence. In 1941, he joined the S. Morgan Smith Company and moved to Rutland, Vermont. There he served as a test engineer and structural analyst.

In 1946, Mr. Holley resigned from the S. Morgan Smith Company to accept a faculty appointment at MIT, in the Civil Engineering Department. There he continued his career as professor, research engineer, and consultant. He retired in 1974 but continues to be very much involved with engineering research and consulting work.

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**Dr. Hurd C. Willett  
Meteorologist**

Dr. Willett's specialty is long-range weather forecasting. He has had a distinguished career at the Massachusetts Institute of Technology extending from 1929 to 1973. His research has centered on the relationship between solar activity and weather. He headed a group of four meteorologists on the Smith-Putnam project. Dr. Willett made many site surveys, frequently alone and in the dead of winter, on mountain tops and ridges of the Green and White Mountains of New England. While the wind turbine was in operation, he prepared weather forecasts as a guide to testing. To do this he analyzed many years of data to identify seasonal changes and stratification characteristics of the wind.

Dr. Willett is Professor Emeritus at MIT and still quite active in professional activities. In 1974 he assisted NASA in the selection of a site on Culebra Island, Puerto Rico, for the 200-kW Mod-0A wind turbine which was installed there. Dr. Willett and his wife reside in Littleton, Massachusetts.

**Wellman Engineering Company  
Cleveland, Ohio  
Principal Designer and Manufacturer**

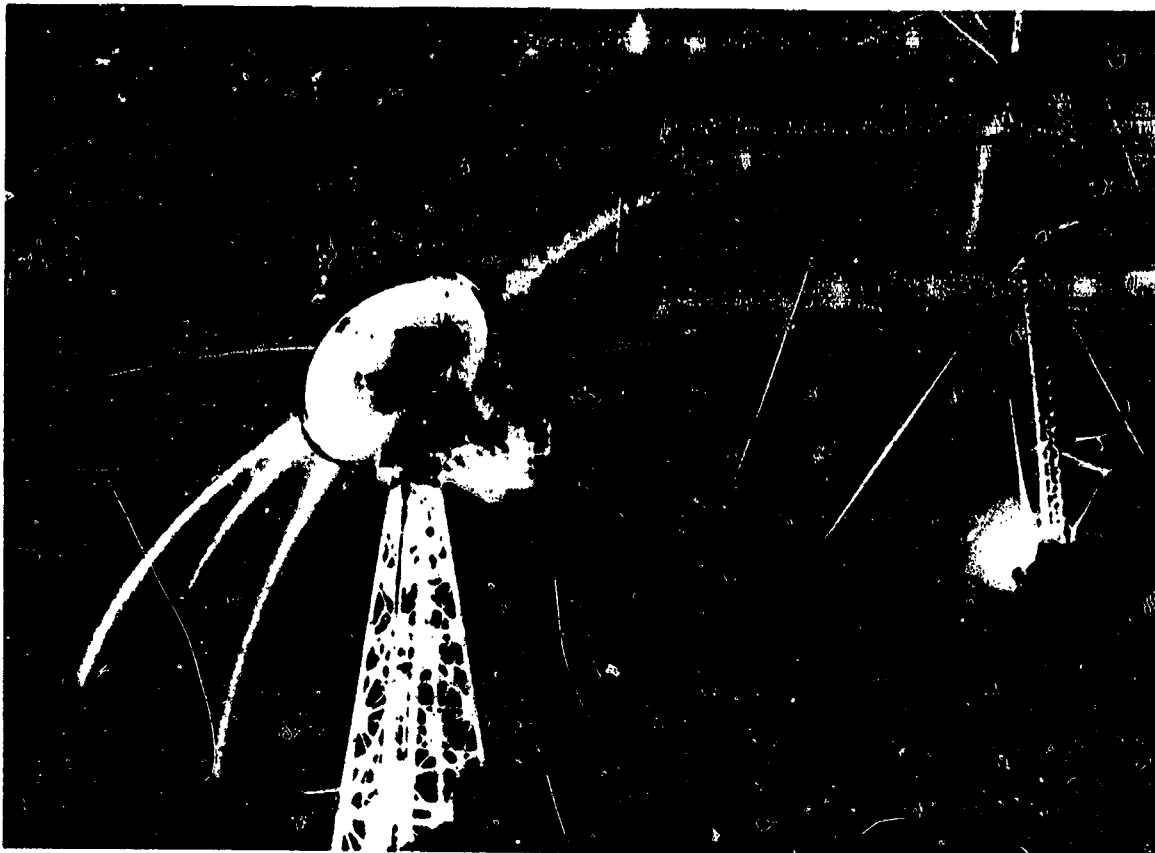
In 1939, the S. Morgan Smith Company selected Wellman Engineering of Cleveland, Ohio, to design, fabricate, and assemble all the equipment in the wind turbine between the tower and the blades. This included the blade A-frame supports with their massive hinges, the rotor hub and turbine shaft, all components of the power train, the blade and power control systems, the bedplate, and the yaw turntable and drive system. All this equipment was assembled and checked out in the company shops in Cleveland in 1941, prior to shipment to Grandpa's Knob.

The Wellman Engineering Company was started in 1896 by Samuel Wellman, a prominent Cleveland industrialist. In the 1930's and 1940's, the firm specialized in the manufacture of heavy equipment for making steel and for handling bulk materials. Mr. Kenneth Webb accepted the citation on behalf of the company which is now known as the Dravo-Wellman Company.

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# The Smith-Putnam Wind Turbine

Reprinted from "Turbine Topics," Volume 1, No. 3, June 1943



*Night Wind*

This reprint has been made available through the courtesy of Carl Wilcox, Smith-Putnam project engineer; the NASA Lewis Research Center; and the U.S. Department of Energy. *Turbine Topics* was a publication of the S. Morgan Smith Co.

# THE SMITH-PUTNAM WIND TURBINE . . .

## A Step Forward In Aero-Electric Power Research

BY GRANT H. VOADEN  
*Asst. Chief Engineer of the Project*

Our company, always in the lead in hydro-electric developments, has been experimenting for the past three years on a new type of unit—an aero-electric unit. Just as a hydro-electric unit consists of a hydraulic turbine driving a generator, so an aero-electric unit is comprised of a wind turbine and a generator.

While some of the experimenting done in the early stages was on small scale wooden models made by our pattern shop, it was necessary to have a full scale unit of large dimensions in order to determine whether the project was feasible from a commercial standpoint. For this purpose the building of such a unit was undertaken and on October 19, 1941, for the first time in history an aero-electric unit was synchronized with, was connected to and delivered power to a commercial, alternating current power system. The photograph on the cover shows the unit in operation at night, the stars appearing as horizontal streaks because of the earth's rotation during the time of exposure. This experimental unit is located on the top of a bare mountain known as Grandpa's Knob, near Rutland, Vermont, and is now owned and operated by the Central Vermont Public Service Corporation.

The inventor of the wind turbine, P. C. Putnam, a Boston engineer, now in our country's service, proposed this project to the Management of our company late in the year 1930. After considerable preliminary study by some of our engineers, aided by consultants such as Dr. Theodore von Karman, Director, Guggenheim Aeronautics Laboratory, California Institute of

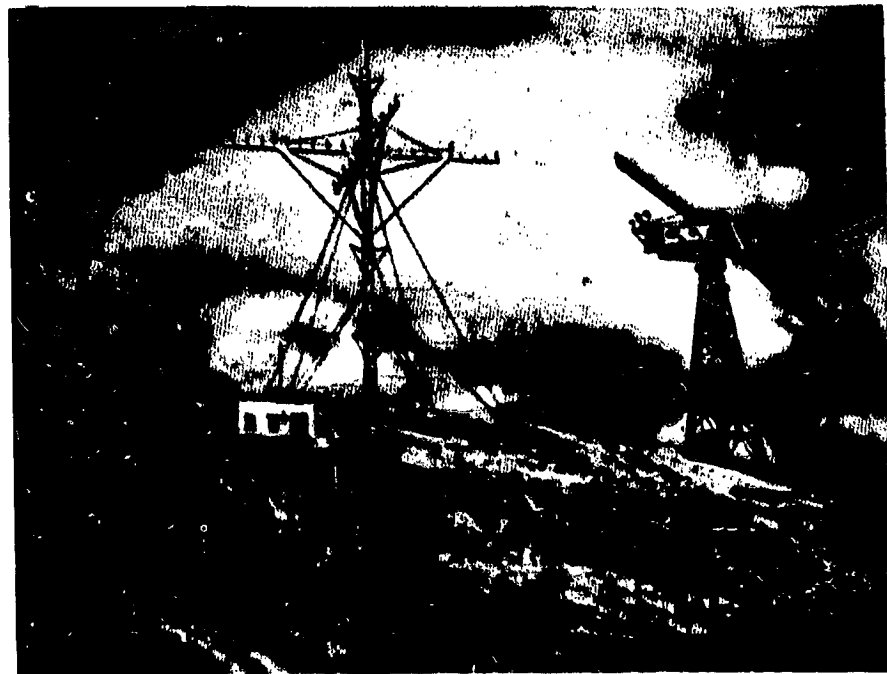
Technology, Dr. S. Petterssen, Aerology Expert of Massachusetts Institute of Technology, now connected with the Norwegian Air Force in England, Dr. John B. Wilbur, Professor of Civil Engineering at M. I. T., and others, the company decided to take up the project. It further decided that the units should be known as Smith-Putnam Wind Turbines and that a test unit should be built of 1,000 K. W. rated capacity, and a blade spread tip to tip of 175 ft.

The fundamental basis of the company's interest was the fact that wind power can be used as an auxiliary to water power. Wind power by itself is not prime power; that is, it is not available all the

time. A wind of about 20 M.P.H.\* is required before any appreciable amount of usable power can be developed. Since sometimes the wind velocity is below this figure there must be other sources of power available to supply the full demand. However, if aero-electric units are added to an existing power system supplied by hydro-electric units or steam driven units or both, then whenever there is sufficient wind a certain number of hydro or steam units can be idled or shut down thereby allowing water to be stored above the dam or coal to be saved.

In the early spring of 1940 Dr. Wilbur accepted the position of

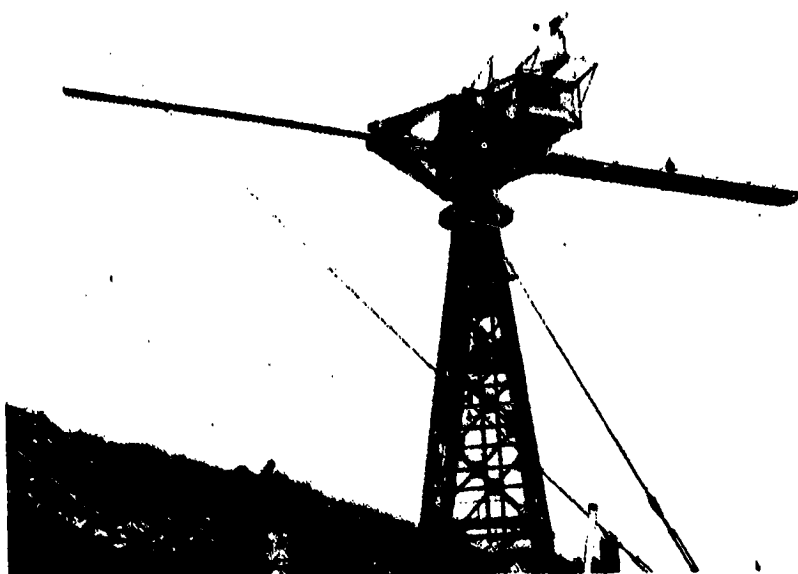
\* This figure can be reduced on future units, depending on the wind regime at the site for which the turbines are built.



SMITH-PUTNAM WIND TURBINE installation on Grandpa's Knob near Rutland, Vt., for Central Vermont Public Service Corp. Tower height, 110 ft., weight 125 tons. Blades 175 ft. tip to tip, speed at tip 263 ft. per second. Weight aloft 240 tons. Mast for anemometers in center to measure wind velocity. Concrete control house, transformers and transmission line to Rutland. Capacity 1,000 K. W.



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THIS IS THE WAY THE WIND TURBINE LOOKS coming up the path from the control house. How would you like to be up there with "Rosie" Rozell?

Chief Engineer of the Project and an engineering force was organized under his direction. Due to the large amount of work in our own plant, the need for speed due to a number of conditions, and the specialized nature of the various phases of the project, it was necessary to have the design and construction of the unit proceed at the same time, and to have the work done by outside concerns. The design and building of practically all the machinery mounted at the top of the tower, with the exception of the blades themselves, was by The Wellman Engineering Company of Cleveland, Ohio. For a few months a staff of over 150 engineers and designers were working full time on the drawings alone. The blades, which are of stainless steel and shaped like the wings of a bomber, were designed and constructed by Budd Manufacturing Company, Philadelphia. The tower on which the turbine proper is mounted and the anemometer mast as well were fabricated of structural

steel and were erected at the site by the American Bridge Company of Ambridge, Pa. The generator and all of the switchgear were designed and furnished by the General Electric Co. Published herewith is a photo of

the complete aero-electric test unit installation on Grandpa's Knob. You see the turbine itself mounted on a structural steel tower 110 ft. high, the concrete control house containing switchboards and instruments for remote control and observation, the transformers and poles for the power line, all of which comprise the station proper. The skeleton-like structure in the center supports anemometers to measure wind velocity and would not be necessary in a purely commercial installation. It is a significant feature from the economic standpoint that the above principal component parts do comprise the entire installation, whereas in a hydro-electric plant it is necessary in addition to have a large dam and power house with expensive auxiliary equipment such as penstocks, head gates, valves, cranes, etc. Then too wind turbines have the advantage that the land which a battery of say 20 units would occupy would be of little value for other purposes, whereas the land area flooded by a dam is usually quite extensive and sometimes of relatively high value.



THESE MEN have just completed a thorough inspection of the stainless steel blade skin.

**TURBINE**

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The turbine proper, which is mounted on the tower, is swung about a vertical shaft by a hydraulic motor and gearing in accordance with changes in wind direction so that the turbine shaft is always in line with the wind direction and the blades downwind of the tower. This motion is called "yawing." The rotation of the turbine about its main shaft axis is right-hand when looking at the turbine with one's back to the wind.

The pitch of the blades themselves, which are only two in number, is changed automatically by a mechanism similar to that on a Kaplan turbine to maintain practically constant speed of rotation regardless of wind velocity. Up to about 18 M.P.H., however, the wind is not high enough to make the turbine rotate at full speed. When that velocity is exceeded the generator is connected to the system and as the wind velocity further increases the turbine gives more and more power without any change in blade pitch until at 30 M.P.H. it has reached the 1,000 K.W. rating of the generator. Beyond this velocity the blades are pitched automatically in response to a Woodward governor to keep from overspeeding and overloading the unit.

Another motion of the turbine is "coning." The blades can move up and downwind pivoting on hinges at the hub under restraint of a damping mechanism. This is to provide some "give" to the mechanism in severe gusts of wind; that is, when the wind either increases or decreases suddenly.

The generator is mounted aloft at the upwind end of the pintle girder and operates at 600 R.P.M., 2,400 volts, 60 cycles, being driven through gears which step up the turbine speed from 28.7 R.P.M. Interposed between these gears and the generator is a hydraulic coupling, similar in principle to a "fluid drive"; its



LEFT TO RIGHT: C. J. Wilcox, P. C. Putman, the inventor, G. A. Jessop, B. E. Smith, Llewellyn Evans, W. P. B., S. D. Dornbirer, J. B. Wilbur, C. L. Avery, Woodward Governor Co., M. G. Dow, Central Vermont public Service Corp., M. J. Holley, Jr.



WIND TURBINE WITH BLADES "FEATHERED." From ground to tip of upper blade in this position is about 205 ft.

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J. B. WILBUR, CHIEF ENGINEER of the Project; Grant H. Voaden, Asst. Chief Engineer of the Project; George A. Jessop, Chief Engineer of the S. Morgan Smith Co.

purpose being to allow a certain amount of "slip" or difference in speed between the high speed side of the gears and the generator itself. At zero load this slip is negligible and the two halves of the coupling rotate at the same speed, but as the load on the generator is increased it is necessary to rotate the driving half coupling faster and faster to overcome the slip until at 1,000 K.W. output its speed is 625 R.P.M. while the generator speed is still 600 R.P.M. While this represents a loss it is necessary for two reasons: primarily to provide means for the loading and unloading of the unit by changing the speed adjustment of the governor and, secondly, to provide a cushion between the turbine and generator to take up shocks due to extremely severe gusts which frequently occur and which otherwise would cause the generator to be thrown off the line due to overload.

The normal control of the unit is completely automatic, even to the phasing with the system, and it functions without attendance. Manual control is also provided. The unit can

be operated completely from the control house several hundred feet from the base of the tower and partially from aloft. This feature is particularly desirable on this first unit for testing purposes.

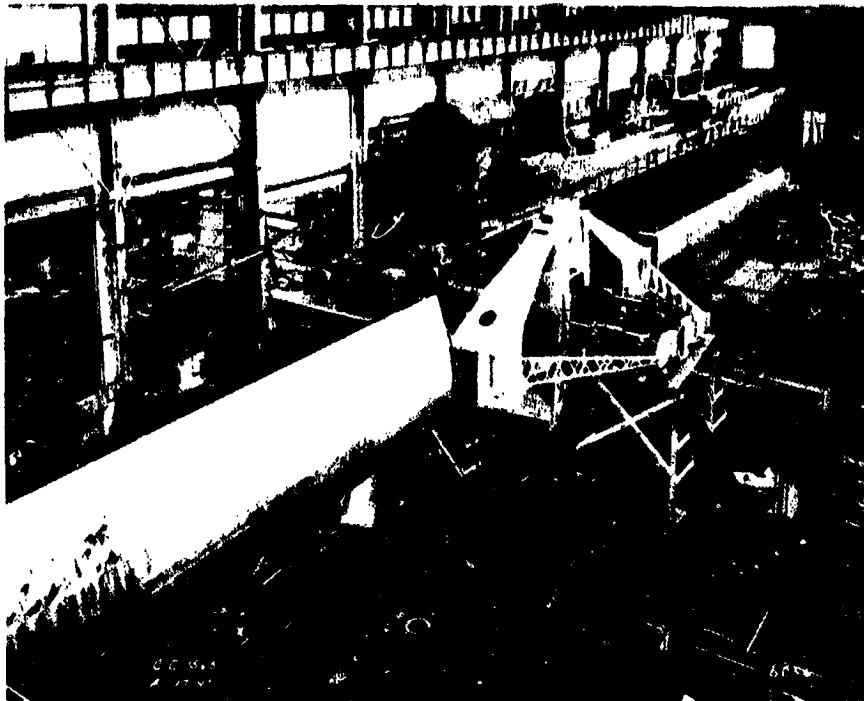


STANTON D. DORNBIER, SUPT. at Erection; Ella Taranovich; Carl J. Wilcox, Office Manager and Test Engineer; Mary Skaza, Myle J. Holley, Jr., Test Engineer; and Arthur H. Cheney who works in our Rutland office.

This project involves a great many fields of engineering knowledge and endeavor; for example, aerology, aerodynamics, mechanics, structural and electrical engineering, to name only a few. Also in the production of these units every type of worker will find a job—pattern makers, boiler makers, welders, pipe fitters, machinists, electricians and mechanics—all are needed. Some of the pictures on these pages illustrate the different types of shop work that are involved in the manufacture of wind turbine. It is confidently expected that some day—and it may not be so long—many more wind turbines will be built right here in our own plant and built from drawings made by our own designers.

As was naturally to be expected in a new machine of such magnitude involving so many novel features, frequent troubles developed which were eventually overcome in the two years since erection was first started. However, the unit has proven itself fundamentally sound and practical. Mechanically it is as satisfactory as

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SHOP ASSEMBLY NEARING COMPLETION in Wellman Engineering Shop, stainless steel blades in position to give maximum power. Note provisions for "coning" of blades up and downwind in gusts, and cylinders and struts for damping the motion.

could be expected with an entirely new design having no basis of past experience. The knowledge gained during the process of bringing this unit to a state of successful operation will enable us to design a production unit which should not only be much improved mechanically, but also be capable of producing power on an economically competitive basis in areas with suitable wind regimes.



ERNEST STUMP, Machinery Erection Foreman.

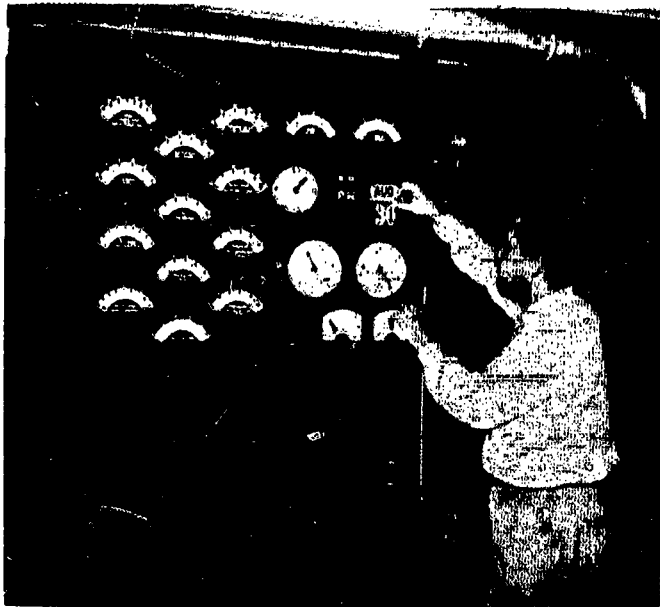


HAROLD S. PERRY, Steel Work Erection Foreman.



ASSEMBLY OF TAILPIECE HUB, A-frame and torque tubes (for pitching the blades). Production Units will have Welded construction, not riveted.

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The views above taken inside the control house show on the left the instrument panel which is special for the test unit, and on the right the switchboard.

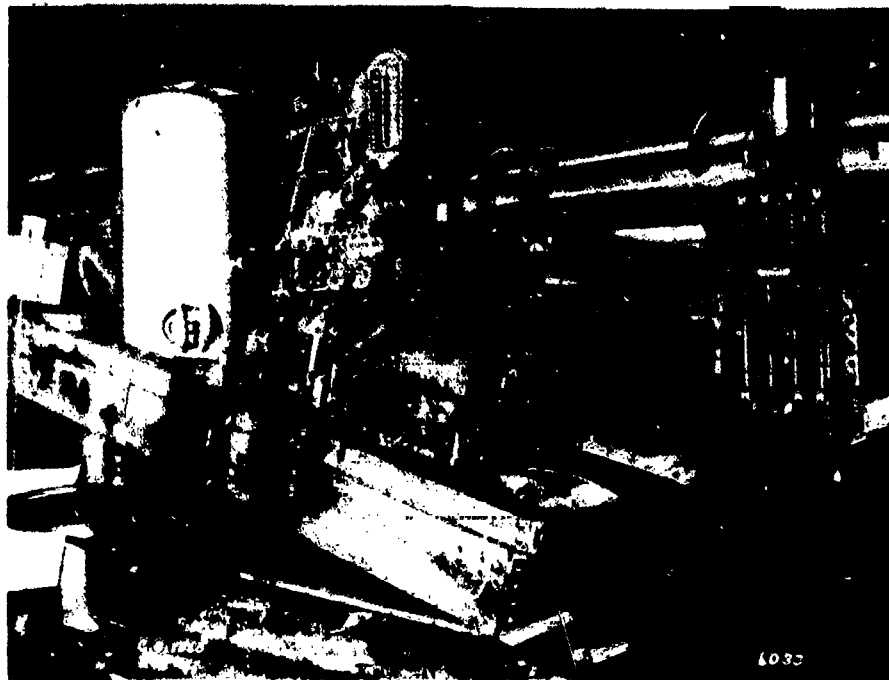
The eighteen instruments on the test panel indicate the functioning of various parts of the unit, which itself is several hundred yards away, and also the wind velocity at a point approximately on the center line of the turbine and fifty feet upwind of the blades. A few of the indications are blade angle, governor speed adjustment, generator output, turbine speed, coning angle, various oil pressures and temperatures. These instruments not only allow the operators and test engineers to know what the unit is doing even though they are on the ground and several hundred feet from the tower, but also provide a means for recording simultaneously all conditions of a test. This is done by an electrically driven motion picture camera which takes pictures of the entire panel continu-



ously whenever the unit is in operation. These films are later projected on a screen and the readings of the various instruments tabulated and test computations made. An elaborate instrument panel like this would not be required on a production unit.

From the control panel, whenever there is sufficient wind, the unit can be manually started, brought up to speed, phased with the system and loaded. Conversely, of course, the

unit can be stopped. Normally, however, all this is done automatically as a function of wind velocity, and the numerous relays, etc., mounted to the right on the larger panel are for this purpose. A 125-volt storage battery provides the basic power for these controls. The right view also shows W. A. Bagley, Switchgear Expert of the General Electric Co., New England District, conducting an Operators' Instruction Class.



PARTIAL SHOP ASSEMBLY showing turbine shaft and outboard roller bearing, oil head, Woodward governor and pump, pressure tank, hydraulic motor and yaw gears all mounted on pintle girder and platform which is mounted on and swings about the top of the tower.

LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Introductory Remarks

"The Federal Wind Energy Program"  
D. F. Ancona III  
Large Wind Energy Technology Branch  
Office of Solar Electric Technologies  
Department of Energy

## THE FEDERAL WIND ENERGY PROGRAM

D. F. Ancona III  
Large Wind Energy Technology Branch  
Office of Solar Electric Technologies  
Department of Energy

There have been significant advances in the Wind Energy Program. In the areas of large machine development, research on wind characteristics, utility interconnection, and environmental concerns, major progress has been made. In addition to the large wind systems, the subject of this workshop, small systems are being tested and being used for power generation by consumers, and several vertical-axis Darrieus systems are being field tested. More importantly, private industry has significantly increased its involvement in the development of wind energy, and, consequently, the Federal role will decrease.

Research into wind characteristics, performed by Pacific Northwest Laboratory, has resulted in the publication of twelve regional wind atlases which document the wind resource in the United States and its territories. A detailed U.S. wind resource map, based on data from the atlases, is shown in figure 1. In addition, the first version of a handbook for siting large wind turbines has recently been published. Studies on the utility issues, addressing economic, legal, and institutional aspects, have been conducted by the Solar Energy Research Institute (SERI). SERI has also investigated and made significant progress in understanding wind turbine noise and local television interference, focusing on the Mod-1 turbine in Boone, North Carolina.

The Small Wind Systems Program has developed a series of wind generators in various sizes for different applications. Three such systems, under test at the Rocky Flats Test Center, are shown in figure 2. The 2 kilowatt machine can be used in remote applications while the 8 kW machine is designed for residences. The 40 kW machine is aimed at agricultural markets. Other designs in these sizes, as well as 4 kW and 15 kW machines, are nearly completed, and commercial sales are mounting.

Progress on the vertical-axis Darrieus wind system has occurred rapidly. Three 17 meter systems have been installed for testing, the first at the Rocky Flats Test Center, the second at a Department of Agriculture site in Bushland, Texas, and the third on Martha's Vineyard, Massachusetts. These machines are performing well and are inherently simple.

We have made great strides in the development of large horizontal-axis wind turbines, which are nearing the point where they can produce cost-

effective electricity in many windy parts of the country. This workshop will focus on the progress made in the development of large machines, such as the first cluster of three Mod-2 turbines shown in figure 3.

In the past year private industry has dramatically increased its wind program activities. Industry is beginning to make significant investments, with many companies planning projects and several building facilities for the manufacture of wind systems and components. Utilities also are initiating major projects. According to an Electric Power Research Institute survey, 91 utilities were involved in 152 projects during 1980, ranging from wind data collection to field testing of small and large systems. These numbers represent the largest increase in any of the new, renewable technologies.

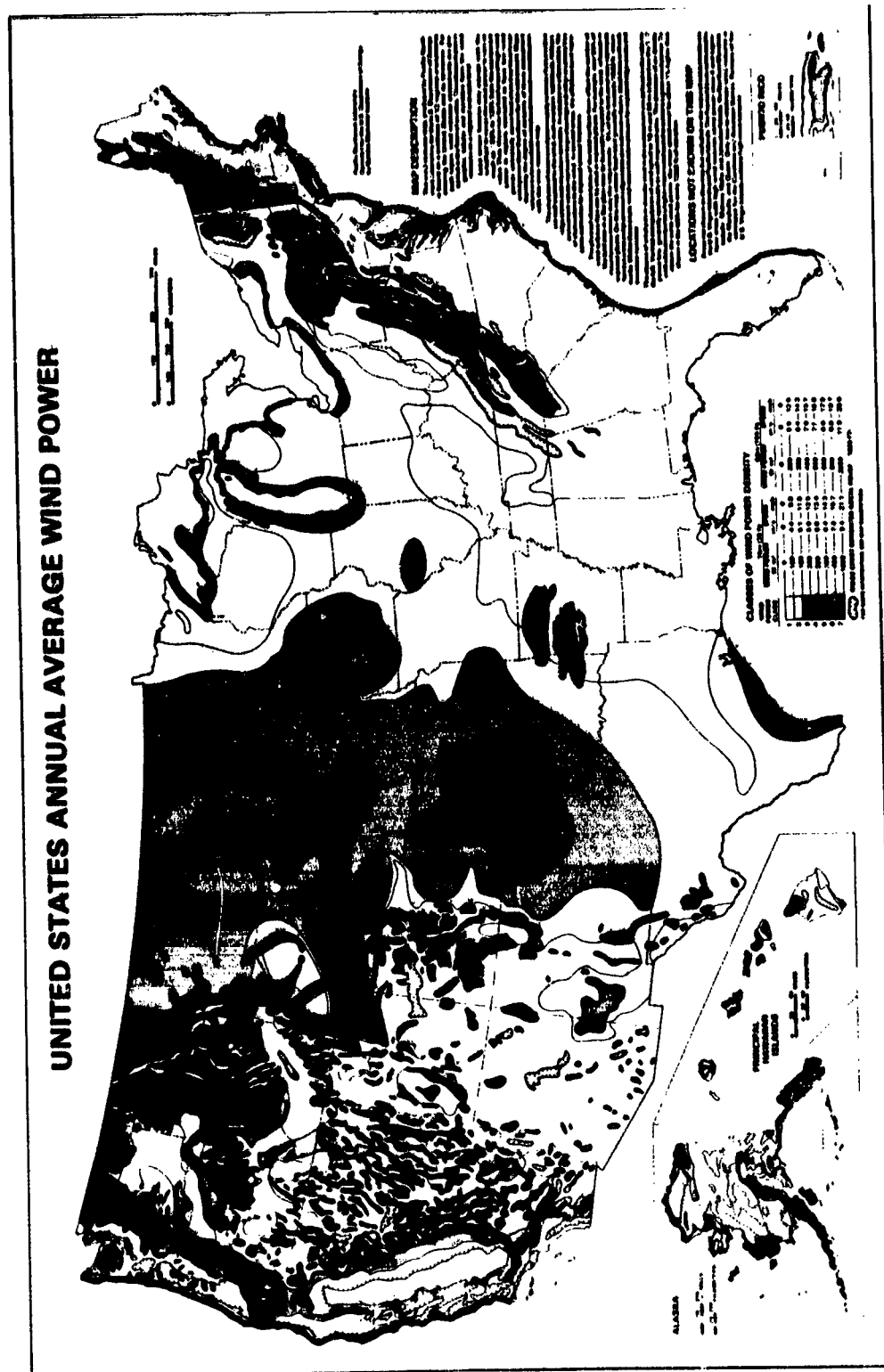
Because industry has shown this interest in wind power, the need for Federal involvement is decreasing. The Federal Wind Energy Program will continue but its efforts have been redirected toward research in high risk, potentially high pay-off areas, and toward studies beneficial to all manufacturers and users.

The Federal Wind Energy Program's objective remains the same--to enable wind energy to be used on a significant scale--but the new thrust of the program is to provide the technology and information base needed by industry (figure 4). Research will continue in several key areas, including aerodynamics, structural dynamics and fatigue phenomena, reliability, and multiple systems interaction. Environmental research, which includes noise and electromagnetic interference, will continue as will research on wind loads, forecasting, and siting methodologies. Areas which will receive less emphasis include systems development, field testing, and market studies. The current budget for the Federal program is decreased accordingly, but this is more than offset by the increased investment by private industry.

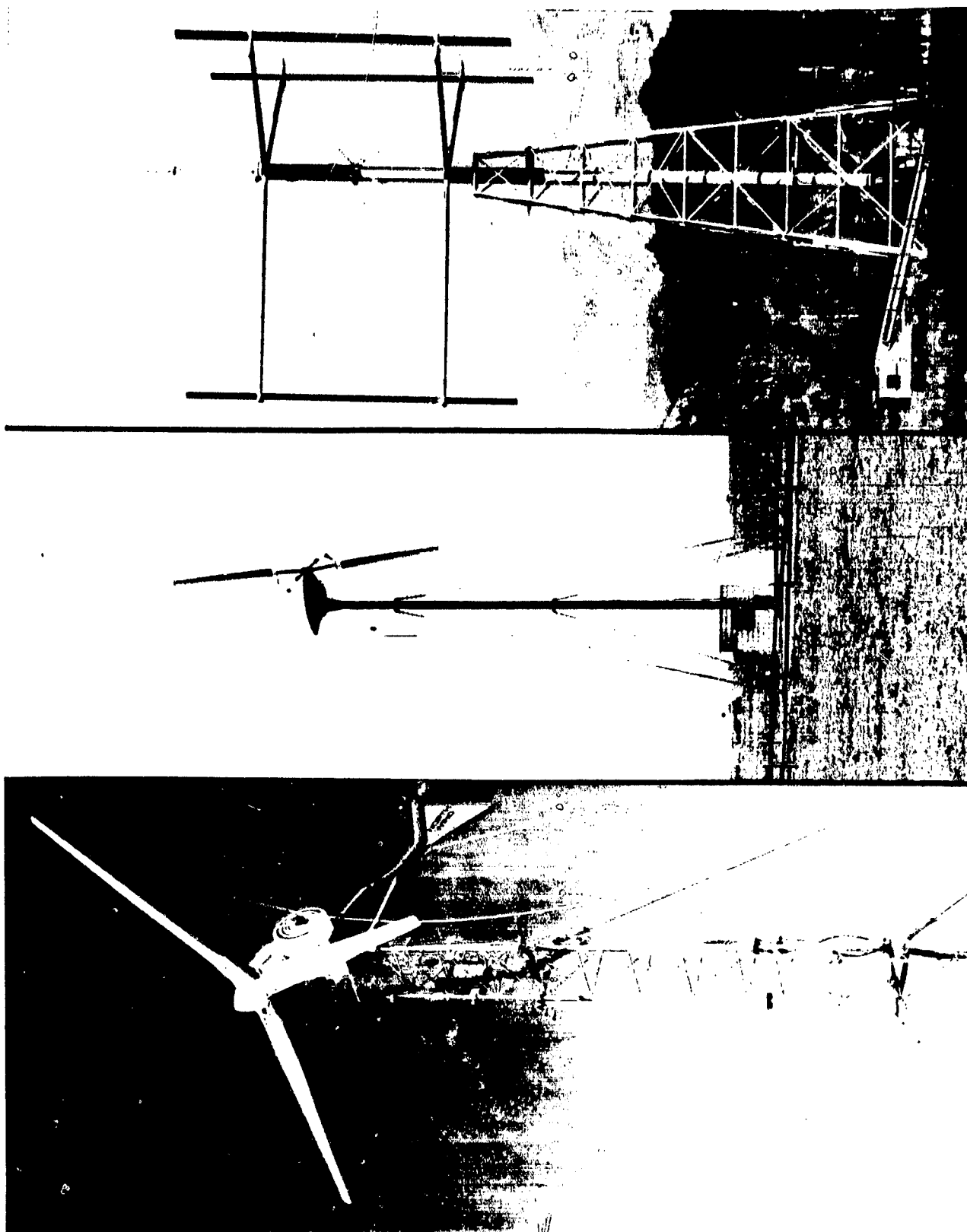
Much work remains to be done by the Federal Wind Energy Program. Its efforts have been redirected, but it will still be a major force in the field as it provides the basic technological information aimed at helping to make wind energy a cost-competitive, viable energy alternative.



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North Wind 2 kW High Reliability

UTRC 8 kW

McDonnell Aircraft 40 kW G1000

FIGURE 2. SMALL WIND SYSTEMS UNDER DEVELOPMENT

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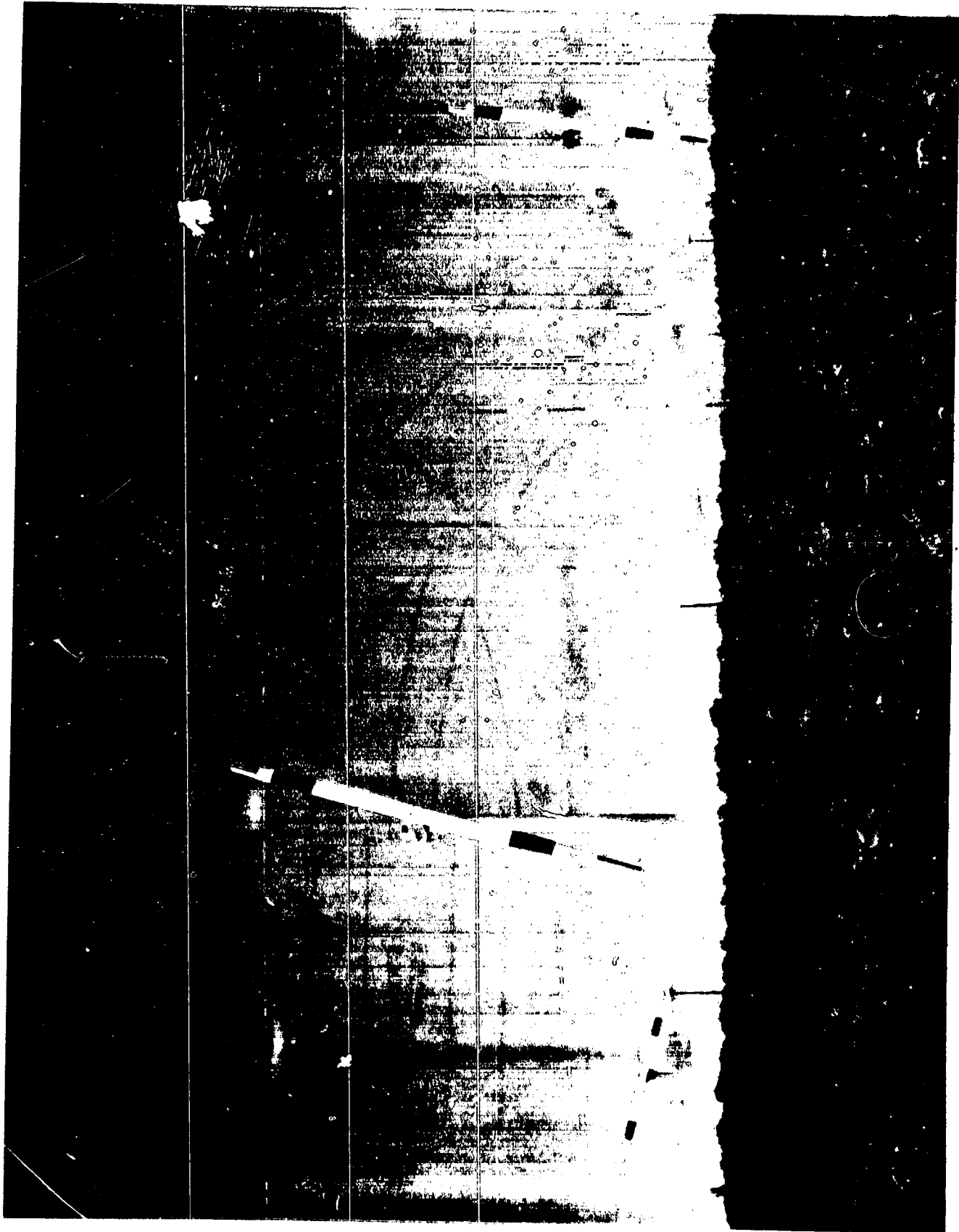


FIGURE 3. MOD-2 WIND SYSTEM CLUSTER

# WIND PROGRAM STRATEGY

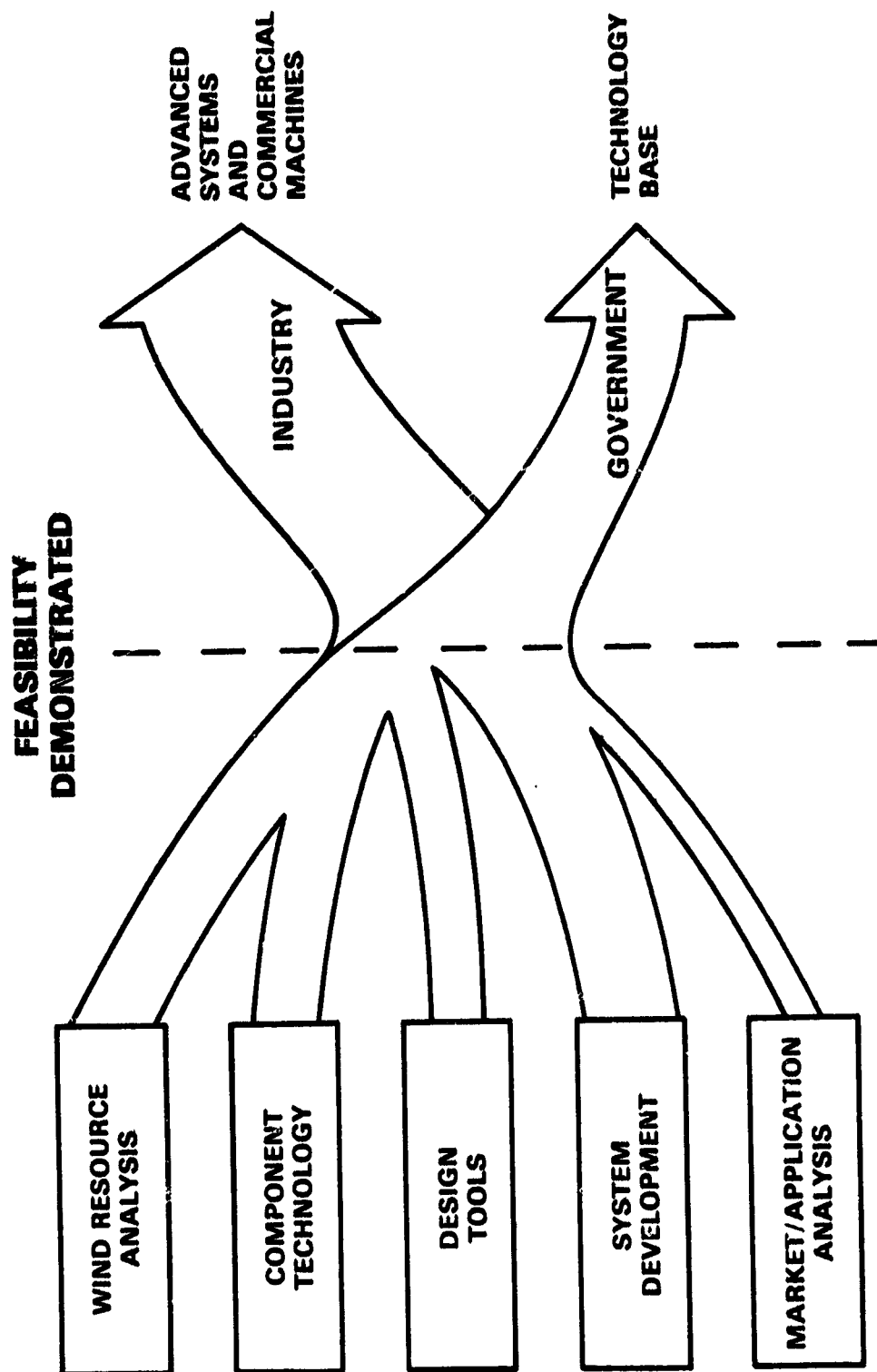


FIGURE 4

LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Research and Supporting Technology

Session Chairman - R. L. Puthoff (NASA LeRC)

"The Response of a 38m Horizontal Axis Teetered Rotor to Yaw"

J. C. Glasgow  
H. G. Pfanner  
E. J. Wentorkamp  
(NASA LeRC)

"Fixed Pitch Rotor Performance of Large Horizontal Axis Wind Turbines"

L. A. Viterna  
R. D. Corrigan  
(NASA LeRC)

"Stall Induced Instability of a Teetered Rotor"

J. C. Glasgow  
R. D. Corrigan  
(NASA LeRC)

"Free Yaw Performance of the Mod-0 Large Horizontal Axis 100 kW Wind Turbine"

R. D. Corrigan  
L. A. Viterna  
(NASA LeRC)

"Multiple and Variable Speed Electrical Generator Systems for Large Wind Turbines"

T. S. Andersen  
P. S. Hughes  
H. S. Kirschbaum  
G. A. Mutone  
(Westinghouse Electric Corporation)

N83 19232 D1

THE RESPONSE OF A 38m HORIZONTAL AXIS  
TEETERED ROTOR TO YAW

J. C. Glasgow, H. G. Pfanner, and E. J. Westerkamp  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

ABSTRACT

Recent tests on the 38m Mod-0 100 kW horizontal axis experimental wind turbine have yielded quantitative data on the teeter response of a rotor to yaw. The test results indicate that yaw rates as high as 5 deg/s could be used in emergency situations to unload and slow a rotor for intermediate sized (500 kW) wind turbines. The results also show that teeter response is sensitive to the direction of yaw, and that teeter response to yaw is reduced as either the rotor speed or the blade Lock number is increased.

INTRODUCTION

A primary concern of designers from the beginning of the use of wind power has been the problem of unloading the rotor and preventing an overspeed in the event of a failure in the drive train or, in recent times, the loss of electrical load on the generator. There are three methods of handling this situation: (1) the blades can be unloaded either by feathering or by use of devices to spoil blade lift and/or increase drag, (2) a brake can be installed to dissipate the energy of the rotor, and (3) the rotor can be yawed or pitched out of the wind to remove the driving force. Until the present, only the first of these methods has been given serious consideration for large wind turbines with a rated power of 100 kW or more. However, with the use of a teetered rotor higher yaw rates can be used and the potential of yaw as a safety procedure has become more attractive. This paper presents results of tests designed to evaluate the effect of yaw on teetered rotor response with a view toward using this maneuver as an emergency safety procedure.

Operating experience indicated the teetered rotor had considerably more tolerance to yaw than did the rigid hub rotor and tests were conducted to determine the maximum yaw rate that could be safely used with a teetered rotor to assess the potential of the yawing maneuver

as a safety device. In addition to this primary objective, the test results were considered to be valuable in that they would provide baseline test data for future analytical studies.

The results presented were obtained from tests conducted on the Mod-0 100 kW experimental wind turbine located at Sandusky, Ohio. Two rotors were tested, one with twisted aluminum blades and the other with untwisted tip-controlled blades having a steel spar as the primary structural member. Both rotors used the same teetered hub and tests were run at rotor speeds of 20 and 31 rpm on the steel spar blades and of 26 rpm on the twisted aluminum blades. Yaw rates were varied from 0.8 to 4.7 deg/s.

#### TEST CONFIGURATION AND PROCEDURE

The teetered rotor yaw tests were conducted on the Mod-0 100 kW experimental wind turbine shown schematically in Figure 1. The essential features of the machine have been described previously [1 and 2]. All tests were conducted in the downwind rotor configuration, i.e., with the rotor downwind of the supporting tower and the rotor axis was tilted 8-1/2 deg to provide tower clearance for the blades. Two rotor configurations were tested; a tip-controlled rotor with untwisted blades and, a fixed pitch rotor with highly twisted aluminum blades. Both rotors were uncone and used the same teetered hub. The blades are described in Table 1 and Figures 2 through 5.

Tests of the tip-controlled rotor were conducted at 20 rpm and at 31 rpm and of the fixed pitch rotor at 26 rpm. Unfortunately the fixed pitch rotor could not be safely tested at 31 rpm due to the danger of exceeding the 100 kW power limit. Also, testing at 20 rpm was inconclusive because of the tendency of the rotor to lose teeter stability in higher wind speeds as the blade began to stall near the tip, and the difficulty in starting the fixed pitch rotor in low wind speeds. The yaw rate was varied by making use of the yaw brake hydraulic power unit which is installed in the nacelle. This unit and the hydraulic yaw drive motor provided capability for yaw rates up to approximately 5 deg/s. A manual flow control valve was used to control yaw rate.

The tests were conducted by first setting a yaw rate, aligning the wind turbine with the wind and yawing the machine 100 deg out of the wind in first the positive and then the negative yaw directions. During the test the generator was synchronized with the utility grid and the overrunning clutch was in the drive train. The overrunning clutch permitted the rotor speed to drop below synchronous speed when the wind load was removed but would not permit the rotor to exceed synchronous speed.

Test data were taken on a strip chart recorder and on magnetic tape. The response of the teetered rotor to yaw of the nacelle was

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determined by analysis of the teeter angle trace. From this time history, the amplitude and phase of the teeter motion was obtained. Teeter angle amplitude was determined by taking a mean of the one-half amplitude of the teeter angles which occurred during a yaw maneuver of 100 deg. Teeter motion is limited by the teeter stops at approximately  $\pm 5.8$  deg; therefore, a mean value of teeter amplitude slightly in excess of 5 deg can involve some teeter stop impacts and a teeter amplitude above 5.5 deg involved teeter stop impacts throughout most of the maneuver.

Phase angle,  $\phi$ , was determined by noting the rotor position at the instant when teeter angle was a maximum for each rotor revolution during the yaw maneuver. Typically, phase angle achieved a steady value during the first five rotor revolutions after the yaw maneuver commenced and maintained a relatively constant value during the remainder of the operation. This relatively constant value is reported as the phase angle for a given yaw rate.

Each data point presented represents an average value obtained from five yaw maneuvers unless the data indicated that excessive teeter stop impacts occurred, in which case the test was not repeated.

Sign Convention and Definition of Terms

Figure 6 presents the sign conventions used at the Mod-0 test facility. Nacelle and wind azimuths,  $\psi_N$  and  $\psi_W$ , are measured in degrees from north. Yaw rate,  $\dot{\psi}$ , is considered to be positive if the nacelle azimuth is increased. Nacelle yaw angle,  $\psi_{NW}$ , is measured relative to the wind. A positive yaw angle results if the nacelle azimuth is larger than the wind azimuth. A positive yaw angle,  $\psi_{NW}$ , is shown in Figure 6.

$$\psi_{NW} = \psi_N - \psi_W$$

Rotor position,  $\phi$ , describes the angle of blade #1 relative to the vertical and down location and is measured in degrees from zero to 360. The rotor direction of rotation is indicated in Figure 1 and by the vector,  $\vec{\Omega}$ , in Figure 6.

The elements essential in describing the motion of a teetered rotor are shown in Figure 7 and are described below. When a rotor is turning in uniform flow without teetering, the blade tips define a circular track in a plane which is perpendicular to the axis of rotation. This plane is called the rotor reference plane. Teeter motion is described by two quantities, maximum teeter angle,  $\theta_{max}$ , and phase angle,  $\phi$ . Positive teeter angle is defined as that teeter angle which causes blade #1 to move upwind of the rotor reference plane and, of course, maximum teeter angle is the largest positive teeter angle during a given rotor revolution. The point of maximum teeter angle is located by a phase angle,  $\phi$ , which describes the angular position of  $\theta_{max}$  relative to the lowest point of the rotor disc. In steady wind conditions, the rotor teeters at a frequency approximately equal to the rotor speed or,



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once per revolution. This produces a tilt in the plane described by the blade tip path relative to the rotor reference plane. Teeter amplitude,  $\theta_{\max}$ , defines the angle the rotor plane makes with the rotor reference plane while the phase angle,  $\gamma$ , defines the orientation of the tilted plane relative to the rotor zero position.

Blade Lock number,  $\gamma$ , is a non-dimensional term used to describe the ratio of air forces to inertia forces for a rotor blade. The term is defined as

$$\gamma = \frac{\rho a_0 c R^4}{I_B}$$

where:

- $\rho$  - air density
- $a_0$  - slope of airfoil lift curve
- $c$  - average blade chord
- $R$  - blade radius at tip
- $I_B$  - blade mass moment of inertia about the rotor center of rotation

Lock number is a measure of the damping of a rotor blade and the term  $\gamma/16$  for a rotor blade has a meaning similar to  $C/C_c$  in damped harmonic motion in that it indicates the nature of the blade's transient response.

## RESULTS AND DISCUSSION

The results of the yaw rate tests are presented in Figures 8, 9 and 10. Figures 8 and 9 present a mean value for the maximum teeter angles,  $\theta_{\max}$ , recorded during the yaw maneuver of 100 deg for each of the yaw rates shown. The teeter angle value is the average of five maneuvers for most of the points. Teeter angle versus yaw rate is shown for two rotors. Figure 10 presents phase angle versus yaw rate for the tip-controlled rotor only.

The tip-controlled rotor at 20 rpm produced higher teeter angles than it did at 31 rpm. This is to be expected because aerodynamic forces, which stabilize the rotor and reduce teeter angle, increase as the square of the tip speed or rotor speed while gyroscopic forces which increase teeter angle with yaw rate increase with the first power of rotor speed. Therefore, increasing rotor speed will increase the permissible yaw rate for a given rotor. Also, rotors with higher Lock numbers should permit higher yaw rates at the same rotor speed.

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This conclusion is indicated in Figure 9 which shows a yaw rate of +4.3 deg/s was required to cause teeter stop impacts on the rotor with aluminum blades, with a Lock number of 11.95, while a yaw rate of only 3 deg/s produced the same result on the rotor with the steel spar blades having a Lock number of 6.56, shown in Figure 8. Also, for negative yaw rates, the mean teeter angle for a given yaw rate was approximately the same for the aluminum blades at 26 rpm and the steel spar blades at 31 rpm. This indicates that lower Lock numbers produce higher teeter angles for the same yaw rate if rotor speed is held constant. Unfortunately, the fixed pitch rotor could not be operated safely at 31 rpm and a direct comparison of the rotors at the same rotor speed was not possible.

There was a definite difference in the teeter response to positive and negative yaw rates, with positive yaw rates producing a higher teeter angle response than negative yaw rates. This is shown clearly in Figures 8 and 9. The reason for this behavior can be understood by examining the phase angle of the rotor during normal operation and during yaw maneuvers of the nacelle.

During normal operation of a downwind teetered rotor aligned with the wind, the phase angle will be at or near 90 deg. This is due to the variation in flow over the rotor disc caused by wind shear and tower interference and the fact that the response of a teetered rotor lags the disturbance by 90 deg. Thus a disturbance occurring when the blades are vertical will be seen when the blades are horizontal. Tower interference and wind shear are most pronounced when the blades are vertical and the response measured by teeter angle is maximum at or near the 90 deg position (which produces a phase angle,  $\phi$ , of 90 deg) and further, since wind speed is higher at the top of the rotor disc, (a blade position of 180 deg) and lower at the lowest point on the rotor disc, the lower, ascending, blade being lightly loaded relative to the upper, descending, blade will cause a teeter motion which brings the tip of the ascending blade into the wind or upwind of the rotor reference plane when the blade is horizontal (see Figure 7).

A second concept is necessary to the understanding of teeter response to yawing motion. When a teetered rotor is yawed, gyroscopic forces resist the motion. These gyroscopic forces on the rotor in a uniform flow would tend to make the rotor have a phase angle and teeter angle of zero if no yaw motion were taking place, a phase angle of +90 deg for yaw in a positive direction and a phase angle of -90 deg for yaw in a negative direction. In this instance, the phase angle and the teeter angle would be created by the tendency of the rotor to remain in its initial plane of rotation.

When the effect of non-uniform flow over the rotor disc is added to the effect of yaw motion, we have a situation which is additive for positive yaw and is cancelling for negative yaw. These effects are indicated by the phase angle versus yaw rate results shown in Figure 10 for the tip-controlled rotor operating at 31 rpm. When the rotor

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operates normally without yawing, a phase angle of 92 deg was measured. For positive yaw rates, the phase angle for operation without yawing is nearly the same as that produced by yawing the machine and the two effects, tower interference and wind shear plus yaw rate, tend to add creating a higher teeter angle and very little change in phase angle.

When the wind turbine is yawed in the negative direction, the two effects tend to counteract one another which results in smaller teeter angles and more tolerance for higher negative yaw rates. In effect, the initial yaw rates are used in changing the phase angle from +90 deg to -90 deg rather than in merely increasing the maximum teeter angle as was the case in yawing the machine in the positive direction. As indicated in Figure 10, the rotor phase angle is changed from +90 deg to -60 deg by increasing the yaw rate to approximately 4 deg/s and the data indicates that negative rates near 5 deg/sec could be tolerated without teeter stop impacts. Thus, a negative yaw rate of approximately 5 deg/s is required for the rotor gyroscopic forces to overcome the effects of non-uniform airflow and create a situation where impacts with the teeter stops could occur.

The test results also indicate the connection between phase angle and rotor response to yaw rates. This implies that the addition of  $S_3$  to the teetered rotor would have an effect on the allowable yaw rate.  $S_3$  is a term taken from helicopter terminology and refers to a method of coupling blade pitch with the teetering of a teetered rotor as indicated in Figure 11.  $S_3$  has an effect on the phase angle,  $\gamma$ , of a teetered rotor and should therefore affect teeter response to yaw. Results have been reported in this area [3], and work is currently underway to extend this effort. These test results and work done previously indicate that yaw could be used as an effective method for removing the load from a rotor under emergency conditions.

## CONCLUSIONS

The results of yaw tests on a 38m horizontal axis teetered rotor indicate the following conclusions:

- o Teeter response to yaw was lower when the wind turbine was yawed in a negative direction.
- o Teeter response to yaw is decreased as
  - (a) Rotor speed is increased
  - (b) Blade Lock Number is increased
- o Yaw rates of 5 deg/s appear to be possible for intermediate size wind turbines with teetered rotors.

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NONENCLATURE

- $a_0$  - slope of airfoil lift curve
- $c$  - average blade chord
- $C/C_c$  - ratio of damping to critical damping for a damped spring mass system
- $I_B$  - blade mass moment of inertia about center of rotation
- $R$  - blade radius at tip
- $V_{wind}$  or  $V_W$  - wind vector
- $\beta$  - teeter angle
- $\gamma$  - Lock number, defined in text
- $\delta_3$  - pitch--teeter angle coupling  
=  $\sin \delta_3$
- $\theta$  - blade pitch angle
- $\tau$  - phase angle, defined in text
- $\rho$  - air density
- $\phi$  - rotor position, angular position of blade #1 relative to vertical, down line
- $\psi_N$  - wind turbine nacelle azimuth
- $\psi_W$  - wind azimuth
- $\psi_{NW}$  - nacelle yaw angle i.e. angle made by nacelle axis and wind vector
- $\Omega$  - rotor speed

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2. Glasgow, J.C., Miller, D.R. and Corrigan, R.D.: Comparison of Upwind and Downwind Rotor Operations of the DOE/NASA 100 kW Wind Turbine  
DOE/NASA/1028-31, NASA TM-81744, 1981.
3. Hohenemser, K.H. and Swift, A.H.P.: Dynamics of an Experimental Two Bladed Horizontal Axis Wind Turbine with Blade Cyclic Pitch Variation. Paper presented at Second DOE/NASA Wind Turbine Dynamics Workshop, Cleveland, Ohio. Feb. 1981.

Table 1 - ROTOR CHARACTERISTICS

<u>Steel Spar, Tip Control Blade</u>	<u>Twisted Aluminum Blade</u>
Rotor dia., m (ft). . 38.39 (126.0)	Rotor dia., m (ft). 38.5 (126.37)
Root cutout, % span . . . . . 23	Root Cutout, % Span . . . . . 5
Tip control, % span . . . . . 30	Fixed Pitch . . . . . --
Blade pitch, inb'd sec., deg. Zero	Blade Pitch 75% Span, deg. . 2.8
Airfoil (inb'd sect.) . NACA 23024	Airfoil . . . . . NACA 230 series
(outb'd 30%). NACA 643-618	(root to tip)
Taper. . . . . Linear	Taper . . . . . Linear
Twist, deg. . . . . Zero	Twist, deg. . . . . 34
Solidity. . . . . 0.033	Solidity. . . . . 0.030
Precone, deg. . . . . Zero	Precone, deg. . . . . Zero
Max. teeter motion, deg. . . . +6	Max teeter motion, deg. . . . +6
Blade mass, kg (lb) . . 1815 (4000)	Blade mass, kg (lb) . 1043 (2300)
Blade Lock number . . . . . 6.56	Blade Lock number . . . . . 11.95

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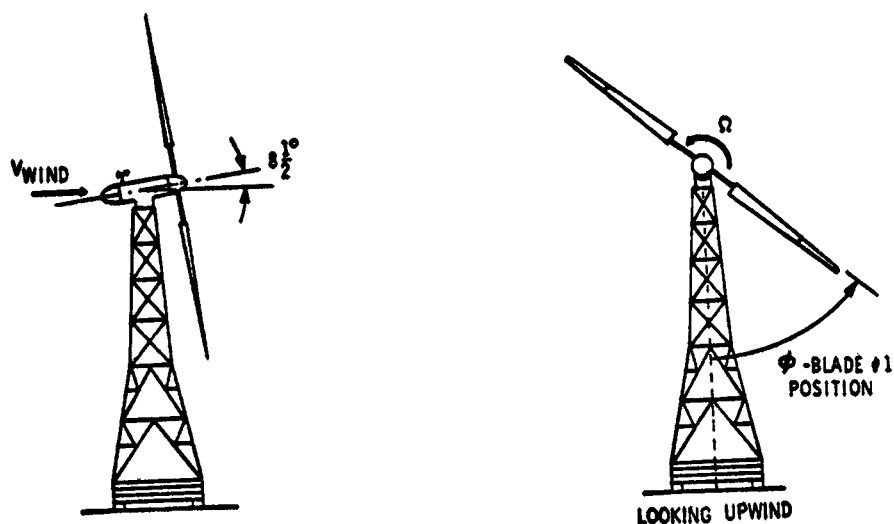
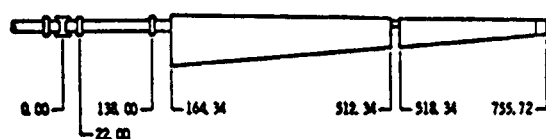
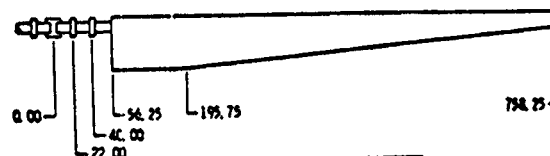


Figure 1. - Mod-0 100 kW Experimental Wind Turbine with Teetered, Tip-Controlled Rotor.



STATION	RADIUS, m	CHORD, m
164.34	4.174	1.964
512.34	13.613	1.171
518.34	13.166	1.154
755.72	18.199	.672

Figure 2. Steel Spar, Tip Control Blade Planform



STATION	RADIUS, m	CHORD, m
96.25	1.43	1.473
195.75	4.97	1.473
754.25	19.25	.657

Figure 3. Twisted Aluminum Blade Planform

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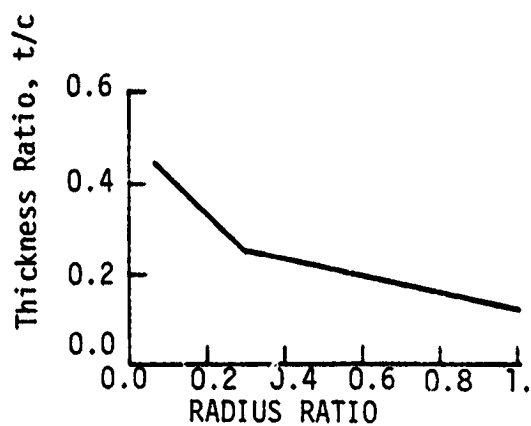


Figure 4. Thickness to Chord Ratio for Twisted Aluminum Blade

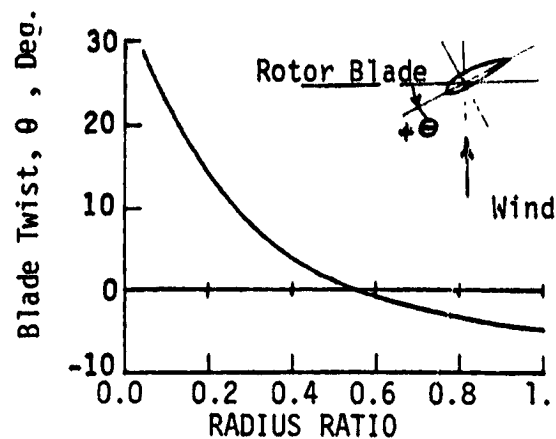


Figure 5. Twist Distribution for Twisted Aluminum Blades

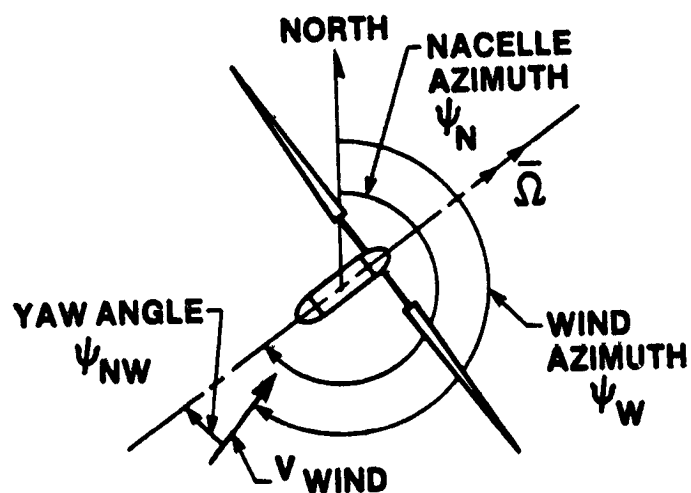


Figure 6. Mod-0 Wind Turbine Sign Convention

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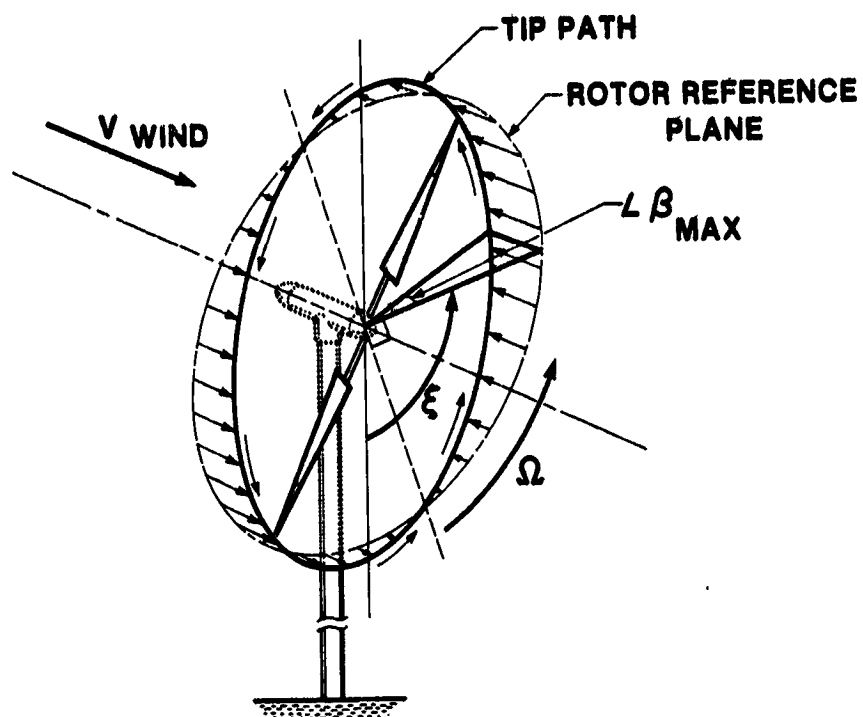


Figure 7. Teetered Rotor Coordinates Showing Maximum Teeter Angle,  $\beta_{max}$ , and Phase Angle,  $\xi$ .

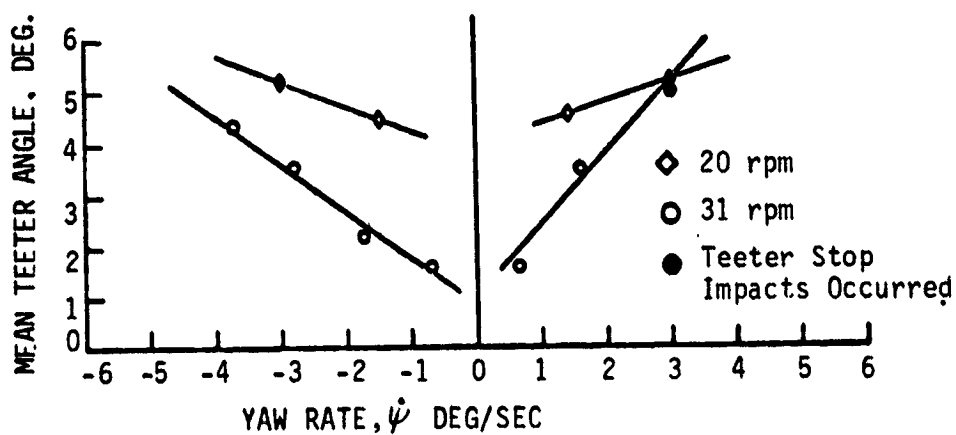


Figure 8. Teeter Angle Versus Yaw Rate for Tip-Controlled Rotor at 20 and 31 rpm.



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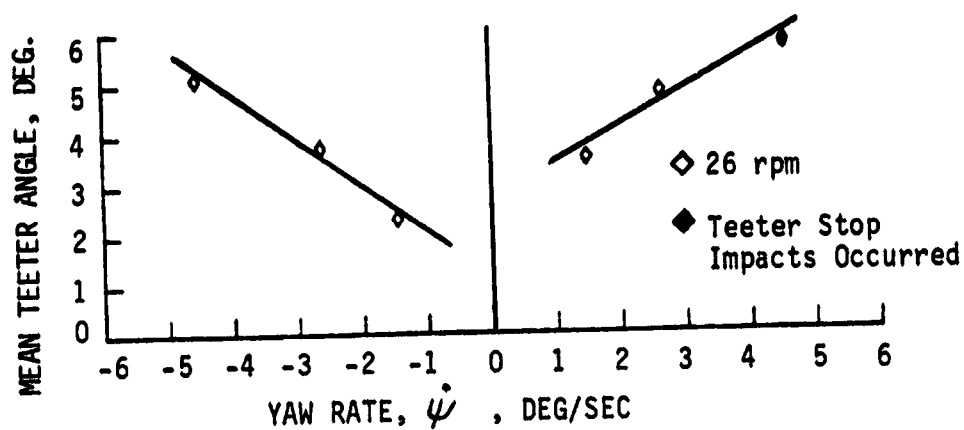


Figure 9. Teeter Angle Versus Yaw Rate for Fixed Pitch Rotor with Twisted Aluminum Blades at 26 rpm

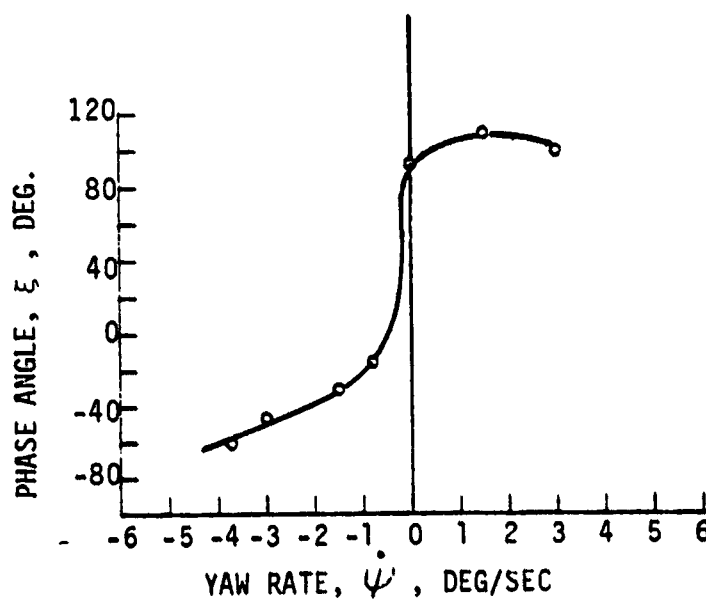


Figure 10. Rotor Phase Angle,  $\xi$ , Versus Yaw Rate for Tip-Controlled Rotor at 31 rpm.

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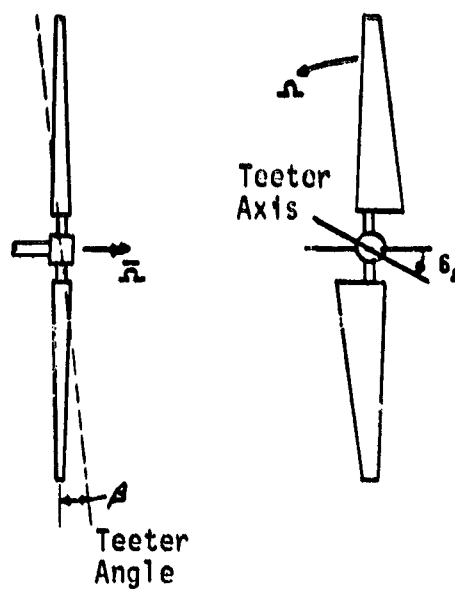


Figure 11. Schematic of Teetered Rotor with  $\delta_3$ . By canting the teeter axis relative to a line perpendicular to the blade axis, blade pitch,  $\Theta$ , is coupled with rotor teeter angle,  $\beta$ , by the relation:  
 $\Theta = \beta \sin \delta_3$ , for small values of  $\beta$ .

QUESTIONS AND ANSWERS

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J. C. Glasgow

From: G. R. Kotloy

Q: Can you explain the action of Delta-3 hinge geometry in suppressing teeter amplitude?

A: *Delta-3 makes the teetered rotor stiffer in that it reduces the teeter response to a disturbance. Delta-3 will also change the phase, which should have an effect on teeter amplitude during yawing maneuvers.*

From: R. Barton

Q: Have you or do you plan to run a transient free yaw from an upwind-loss of load condition (i.e. MOD-2)?

A: *No, we have not run this case but measurements of yaw moment for a teetered upwind rotor indicate the machine is unstable in this mode. However, teetered rotors in free yaw appear to respond very slowly in yawing to a desired zero load condition and the test would probably be very well behaved.*

From: A. Swift, Jr.

Q: Have you considered yaw control for power or torque control above the rated wind speed or only for emergency shutdown? Is 5° per second sufficient for power control (for fixed pitch-aluminum twisted blades)?

A: *We have considered this but the test results to date indicate that the response would be poor for "up gusts" while operating at the rated wind speed and aligned with the wind. In this condition about 30° of yaw would be required before significant power could be shed.*

From: S. Oye

Q: What was the actual Delta-3 angle during your experiments?

A: *The Delta-3 angle was zero degrees.*

From: C. Rybak

Q: What is the teeter angle sensitivity to yaw error or yaw rate?

A: *This data is presented in a report "Teetered, Tip Controlled Rotor: Preliminary Test Results," reference 1 above. These data indicated higher teeter angles for positive yaw angles, but no trend, i.e. flat for zero and negative yaw angles.*

J. C. Glasgow (continued)

From: A. Swift, Jr.

Q: Why do the teeter angle response lines not extrapolate to zero at zero yaw rate and why do the lines of response extrapolate to difference values for different yaw rate directions?

A: *The lines should extrapolate to the same value at zero yaw rate. The data shown should not include the  $\pm 4.5^\circ$  per second point with teeter stop impacts, see Figure 9. The teeter stop reduced the teeter amplitude for this point. Using only the first two positive yaw rate points will produce the correct result, approximately equal teeter amplitude at zero yaw rate.*

FIXED PITCH ROTOR PERFORMANCE OF  
LARGE HORIZONTAL AXIS WIND TURBINES

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Cleveland, Ohio

ABSTRACT

Experimental fixed pitch wind turbine performance data is presented for both the DOE/NASA Mod-0 and the Danish Gedser wind turbines. Furthermore, a method for calculating the output power from large fixed pitch wind turbines is presented. Modifications to classical blade element-momentum theory are given that improve correlation with measured data. Improvement is particularly evident in high winds (low tip speed ratios) where aerodynamic stall occurs as the blade experiences high angles of attack.

INTRODUCTION

Recent tests on the NASA Mod-0 100kW wind turbine indicate that classical blade element-momentum theory is inadequate when the airfoils are at high angles of attack. This problem is particularly important in the calculation of fixed pitch and tip control rotor performance. Since the maximum power produced by a fixed pitch rotor is a critical design parameter, efforts are being made to improve theoretical analysis of this operating condition.

Experimental data from two Mod-0 rotor configurations as well as from the Danish Gedser wind turbine were analyzed. An empirical correction to the aerodynamic characteristics is presented which shows good agreement with the experimental results.

EXPERIMENTAL DATA

Tests were run on the NASA Mod-0 100 kW wind turbine to investigate the performance characteristics of fixed pitch rotors. Two rotors were used in the Mod-0 tests, both of which were 38 meters in diameter. Details of the blade planform, twist, etc. are given in Tables 1a and 1b and Figures 1a and 1b. Significant differences between the two blades are that the aluminum blades have a variable

thickness to chord ratio ( $t/c$ ) and 34 degrees of non-linear twist, while the steel spar blades have a constant  $t/c$  and no twist. The thickness and twist distributions for the aluminum blades are given in Figures 2a and 2b.

The Mod-0 wind turbine was operated with the highly twisted aluminum blades at nominal rotor speeds of 20 and 26 rpm. Due to slip of the fluid coupling in the drive train, actual rotor speeds were 21.0 and 27.4 rpm at the maximum power of 50 kW and 105 kW respectively. Alternator output power and reference windspeed were recorded on magnetic tape and analyzed using the method of bins [ref. 1]. Figure 3 shows the median measured output power versus reference windspeed. The reference windspeed is measured by an anemometer located at hub height about 60 meters upwind of the rotor. This location is believed to give windspeeds which are representative of the average freestream windspeed at the rotor. The most interesting characteristic of the curves is the relatively constant output power at high windspeeds for both rotor speeds. The leveling off of the power output occurs for wind speeds at which stall occurs over most of the blade. Maximum power is greater for the higher rotor speed since higher wind speed is required to achieve the same stall angle of attack.

Further tests were conducted using the steel spar blades with no twist. The rotor speed was 32 rpm. The inboard 70 percent of the blade remains fixed in pitch and thus experiences high angles of attack at high windspeeds. As the wind speed increases, the wind turbine power output increases until the generator rating of 100 kW is reached. When wind speed increases further, it is necessary to pitch the outboard blade section so that the generator rating will not be exceeded. The tip pitch angle versus nacelle windspeed is given in Figure 4. The nacelle wind speed is measured by an anemometer located on the wind turbine nacelle. As shown in Figure 4, the outboard section pitching continues to increase as wind speed increases. This data indicates a continuing production of torque by the inboard fixed pitch portion, of the blade even though that section is stalled.

Finally, performance data from the fixed pitch Gedser wind turbine [ref. 2] is presented in Figure 5. Table 2 and Figure 6 present the rotor configuration for this wind turbine which operated in Denmark beginning in 1957. Though not much data was recorded for very high winds, operators of the Gedser turbine also reported constant power at windspeeds above stall.

### Classical Theory

Blade element-momentum theory used in the PROP Code [ref. 3], as well as others, divides the blade into small spanwise elements. These elements are each considered to act as airfoil segments in two-dimensional flow fields, each at a particular angle of attack. From the geometry, the rotational velocity component, the wind

component, and the "induced" axial and rotational components, the local angle of attack is calculated. The lift and drag forces on the elements are then determined from two-dimensional (infinite aspect ratio) wind tunnel data at the local angle of attack [ref. 4]. Comparison of cambered and uncambered data indicates little difference in airfoil performance beyond stall. Therefore, data for symmetric sections may be used [ref. 5, 6]. The "induced effects" of the wind turbine on the flow are determined in an iterative procedure until momentum theory is satisfied. The end effects of the finite length wind turbine blade are included by using a tip loss model. There are a variety of these tip loss models, the simplest being to reduce the lift coefficient to zero for approximately 3 percent of the radius near the tips. A more complete description of blade element-momentum theory, is contained in reference 3.

The Mod-0 aluminum blade rotor was modelled with the PROP Code. The aerodynamic data used is given in Figure 7 for a NACA 23018 "half-rough" airfoil. The designation "half-rough" denotes aerodynamic data which is an average of NACA smooth and rough data given in reference 4. This roughness effect was included to account for manufacturing imperfections and for the accumulation of dirt as the airfoil is exposed to the environment.

Since the output of the PROP Code is rotor power with no drive train losses, the following drive train efficiency model based on experimental data was used to calculate the electrical power:

$$(1) \quad P_3 = -1.932 + 0.8238 P_2$$

in which  $P_3$  is the electrical power, (kW) and  $P_2$  is the rotor power, (kW).

Figure 8 shows the predicted power versus windspeed for the Mod-0 aluminum blades using the PROP Code. The correlation between measured data and analysis using infinite aspect ratio airfoil data is not very good. Similar results were obtained for the Mod-0 steel spar blade [Figure 9] and the Gedser wind turbine [Figures 10]. Smooth airfoil data was used for the Gedser wind turbine since standard rough data was not readily available for the its airfoil (Clark-Y). The most apparent deficiencies of the predicted results are (1) the rapid increase in power before stall, (2) the less-than-measured maximum power, and (3) the decrease in power after stall.

#### Improved Model

By manipulation of the airfoil characteristics the PROP Code was able to match the measured performance of the Mod-0 and Gedser wind turbines. A reduction in the unstalled lift curve slope, an increase

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in the drag coefficient before stall, and a decrease in the drag coefficient after stall were required. It was observed that the resulting airfoil characteristics were approximately the same as those of a finite length wing with the same aspect ratio.

The formulas for converting infinite length airfoil data to finite length data are from the work of Munk, Glauert, and Prandtl. The equations are [ref. 7] given by the following:

$$(2a) \quad C_L = C_{L0}$$

$$(2b) \quad C_D = C_{D0} + \frac{C_L^2}{\pi AR} (1 + \sigma)$$

$$(2c) \quad \alpha = \alpha_0 + \frac{57.3 C_L}{\pi AR} (1 + \tau)$$

in which:

- $C_L$  is the lift coefficient
- $\alpha$  is the angle of attack, deg
- $C_D$  is the drag coefficient
- $AR$  is the aspect ratio
- $\tau, \sigma$  are factors to allow for the change from elliptical span loading to an airfoil with rectangular loading
- $0$  is a subscript denoting infinite aspect ratio data

The actual aerodynamic load distribution on a wind turbine blade varies with windspeed, twist, planform, etc. However, since the factors  $\tau$  and  $\sigma$  are small, the loading has been assumed elliptical ( $\tau, \sigma$  are zero). The above corrections are made to the airfoil data below stall. Furthermore, because the end effects of the blade have been accounted for in the airfoil characteristics, the tip loss model has been eliminated.

It should be noted that the above corrections are empirical. The use of airfoil characteristics for infinite span in classical theory is regarded as established. The fact remains, however, that classical theory appears incapable of predicting performance at high angles of attack which occur for low aspect ratio blades at low rotor tip speed ratios. In the extreme, for example, at a tip speed ratio of zero (0 rpm) classical theory would predict the thrust on the rotor to be proportional to the drag coefficient of about 2 for an infinite aspect ratio [ref. 5]. We know, however, this is not true. The drag coefficient for even a flat plate of aspect ratio 8 is less than



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1.3 [ref. 8]. It could be that assumption in momentum theory of an infinite number of lightly loaded blades needs to be reassessed and improved theoretical models developed for this condition.

Investigation of the airfoil characteristics after stall reveals the reason for the predicted negative power at very high winds. Figure 11 shows an airfoil element operating with its chord line parallel to the plane of rotation (as on the steel spar rotor). The resultant wind velocity acts at an angle of attack,  $\alpha$ , with respect to the plane of rotation. The coefficients of lift,  $C_L$ , and drag,  $C_D$ , forces operating on the element can be resolved into a coefficient of torque force,  $C_Q$ , which acts in the plane of rotation. This coefficient is given by

$$(3) \quad C_Q = C_L \sin \alpha - C_D \cos \alpha$$

Using the infinite aspect ratio data from Figure 7 it can be seen in Figure 12 that negative torque can be expected for angles of attack between stall and 45 degrees.

The airfoil characteristics after stall were determined for an idealized stall which would result in constant power (torque) at high angles of attack. The torque force on a blade element is proportional to the coefficient of torque force and the square of the resultant velocity or mathematically

$$(4) \quad Q \sim C_Q V_R^2$$

For a constant rotor speed we can divide by the constant  $V_\Omega^2$  which yields

$$(5) \quad Q \sim C_Q \frac{V_R^2}{V_\Omega^2}$$

but from Figure 11

$$\cos \alpha = V_\Omega / V_R$$

and thus

$$(6) \quad Q \sim \frac{C_Q}{\cos^2 \alpha}$$

Substituting Eq. (3) gives

$$(7) \quad Q \sim \frac{C_L \sin \alpha}{\cos^2 \alpha} - \frac{C_D}{\cos \alpha}$$

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If we let

$$(8) \quad C_L = A_1 \sin 2\alpha + A_2 \frac{\cos^2 \alpha}{\sin \alpha}$$

and

$$(9) \quad C_D = B_1 \sin^2 \alpha + B_2 \cos \alpha$$

and substitute into Eq. (7) we have

$$(10) \quad Q \sim (2A_1 - B_1) \sin \alpha \tan \alpha + (A_2 - B_2)$$

Since the measured torque after stall is independent of wind speed it must also be independent of angle of attack. Thus, taking the derivative with respect to  $\alpha$  and setting it equal to zero yields

$$(11) \quad A_1 = \frac{B_1}{2}$$

Referring to Figure 13, at an angle of attack of 90 degrees equation (9) gives

$$(12) \quad B_1 = C_{D\text{MAX}}$$

For a finite aspect ratio blade

$$(13) \quad C_{D\text{MAX}} \simeq 1.11 + 0.018 R$$

for  $R \leq 50$  based on experimental data from Reference 8.

Thus

$$(14) \quad A_1 = \frac{C_{D\text{MAX}}}{2}$$

Rearranging Eq. (8) and substituting Eq. (14) yields

$$(15) \quad A_2 = (C_L - C_{D\text{MAX}} \sin \alpha \cos \alpha) \frac{\sin \alpha}{\cos^2 \alpha}$$

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Similarly Eqs. (9) and (12) give

$$(16) \quad B_2 = \frac{C_D - C_{D\text{MAX}} \sin^2 \alpha}{\cos \alpha}$$

For continuity with the below stall airfoil data,  $A_2$  and  $B_2$  are solved at the stall angle condition and thus Eqs. (15) and (16) become

$$(17) \quad A_2 = (C_{L_s} - C_{D\text{MAX}} \sin \alpha_s \cos \alpha_s) \frac{\sin \alpha_s}{\cos^2 \alpha_s}$$

and

$$(18) \quad B_2 = C_{D_s} - \frac{C_{D\text{MAX}} \sin^2 \alpha_s}{\cos \alpha_s}$$

in which the subscript  $s$  denotes the value of the constant at stall.

The resulting airfoil characteristics for a NACA 23018 airfoil with an aspect ratio of 25 are given in Figure 14 and 15 along with the characteristics for an infinite aspect ratio airfoil [Fig. 8]. With these corrections to the airfoil characteristics, the predicted performance of the Mod-0 aluminum blade is found to correlate well with the measured data as shown in Figure 16. Similar results were obtained for the Mod-0 steel spar blade and the Gedser wind turbine are shown in Figures 17 and 18.

## CONCLUSIONS

A method of correcting the airfoil characteristics for use with blade element-momentum theory has been developed. The airfoil data below stall is corrected for the finite length of the blade. This approach appears to account for the induced effects better than classical blade element-momentum theory alone, particularly for highly loaded low aspect ratio blades. An idealized model for aerodynamic characteristics after stall has been developed which results in nearly constant power in high winds. This model shows good agreement with experimental data from two rotor configurations on Mod-0 as well as the Danish Gedser wind turbine.

## NOMENCLATURE

$A$	aspect ratio of blade, $R/c$ , based chord length at 75 percent radius
$A_1, A_2$	constants in lift coefficient equation after stall
$B_1, B_2$	constants in drag coefficient equation after stall
$c$	chord length, m
$C_D$	drag force coefficient
$C_{Dmax}$	drag force coefficient at $90^\circ$ angle of attack
$C_L$	lift force coefficient
$C_Q$	torque force coefficient
$P_2$	rotor output power, kW
$P_3$	electrical output power, kW
$Q$	torque force, N
$r$	local radius, m
$R$	radius of rotor blade, m
$V_R$	resultant velocity vector, m/s
$V_0$	free-stream wind speed, m/s
$V_1$	wind velocity at rotor plane, m/s
$V$	velocity due to rotation, m/s
$\alpha$	angle of attack, deg
$\tau \quad \sigma$	factors to allow for the change from elliptical span loading to an airfoil with rectangular loading
$0$	denotes infinite aspect ratio airfoil data
$s$	value of airfoil characteristic at stall

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7. Jacobs, E.M. and Abbot, I.H., "The NACA Variable-Density Wind Tunnel," NACA TR 416, 1932.
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TABLE 1a

ALUMINUM BLADE CHARACTERISTICS

Rotor dia., m(ft)	38.5 (126.4)
Number of Blades	2
Root cutout, % span	5
Fixed Pitch	--
Airfoil	NACA 230 Series
Taper	Linear
Twist, deg	34 (Non-linear)
Solidity	0.031
Precone, deg	0
Tilt, deg	8.5

TABLE 1b

STEEL SPAR BLADE CHARACTERISTICS

Rotor dia., m(ft)	38.4 (126.0)
Number of Blades	2
Root Cutout, % span	23
Tip Control, % span	30
Blade Pitch 75% span, deg	0
Airfoil	NACA 23024
Taper	Linear
Twist, deg	0.033
Precone, deg	0
Tilt, deg	8.5

TABLE 2

GEDSER BLADE CHARACTERISTICS

Rotor dia, m(ft)	24 (28.7)
Number of Blades	3
Root cutout, % span	25
Fixed Pitch	--
Blade Pitch 75% span, deg	6
Airfoil	Clark-Y
Taper	None
Twist, deg	12 (Linear)
Solidity	0.090
Precone, deg	0
Tilt, deg	10

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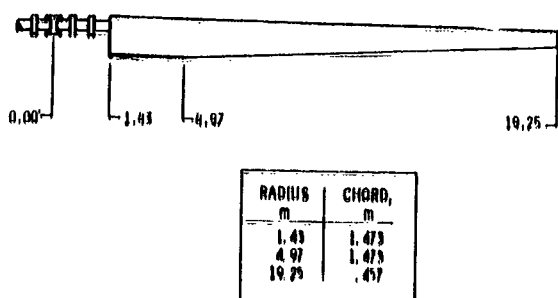


Figure 1a - Mod-0 aluminum  
blade planform

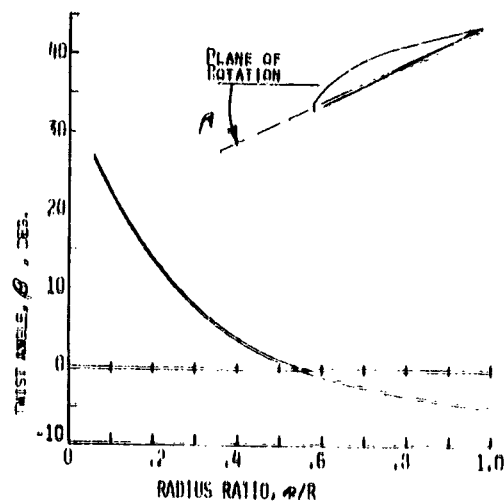


Figure 2b - Mod-0 aluminum  
blade twist distribution

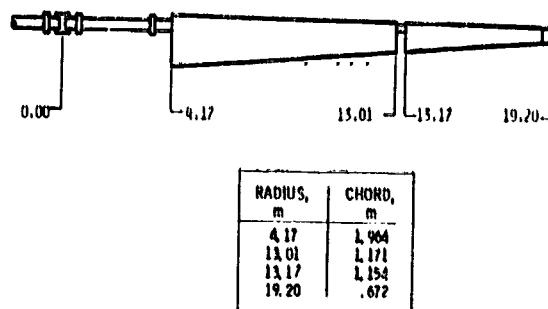


Figure 1b - Mod-0 steel spar  
blade planform

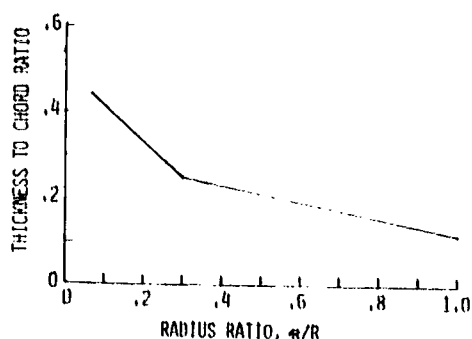


Figure 2a - Mod-0 aluminum  
blade thickness to chord  
ratio distribution

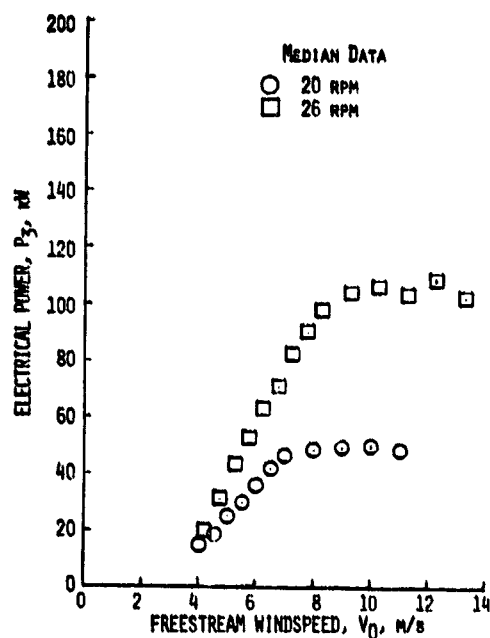


Figure 3 - Measured Performance  
of the Mod-0 aluminum  
blades at 20 and 26 rpm

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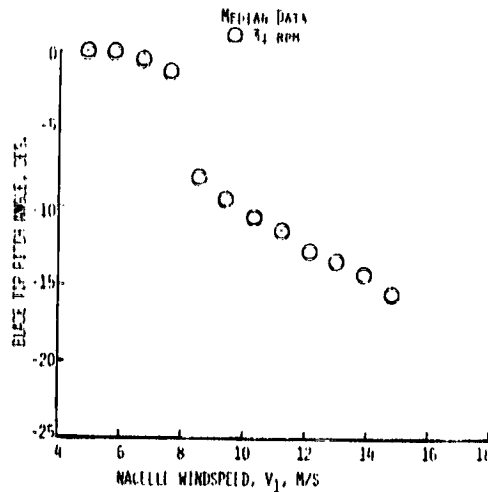


Figure 4 - Measured tip pitch angle versus windspeed for the Mod-0 steel spar, tip control blades

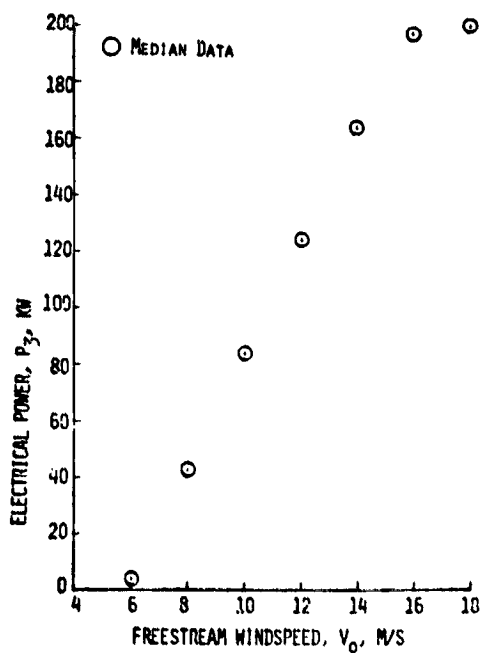


Figure 5 - Measured performance of the Danish Gedser wind turbine

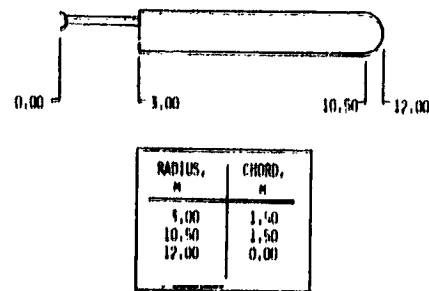


Figure 6 - Danish Gedser wind turbine blade planform

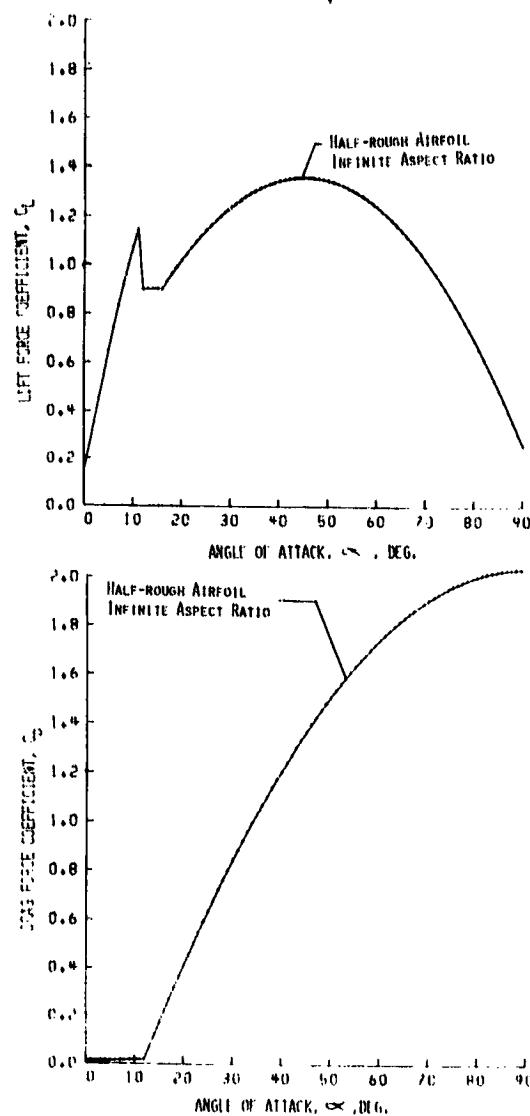


Figure 7 - Aerodynamic data for "half-rough" NACA 23018 airfoil



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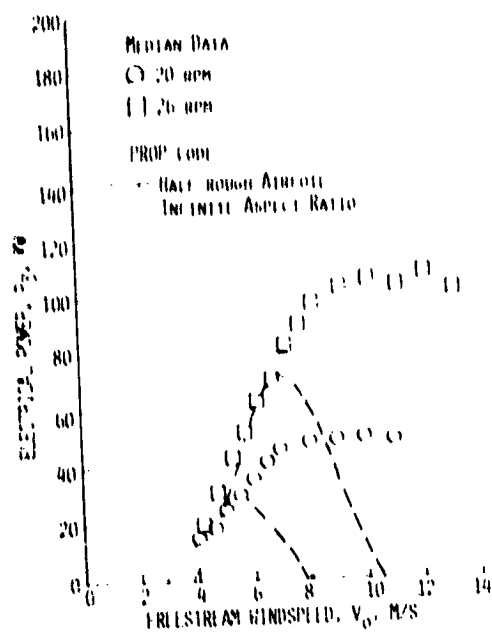


Figure 8 - Comparison of measured and calculated performance using classical theory for the Mod-0 aluminum blades

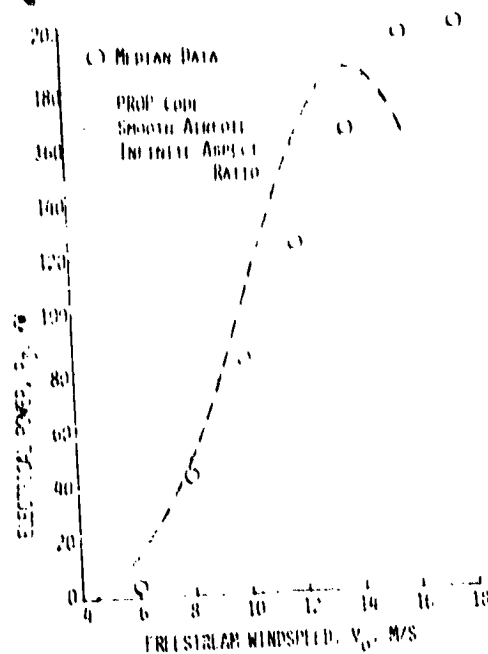


Figure 10 - Comparison of measured and calculated performance using classical theory for the Danish Gedser wind turbine

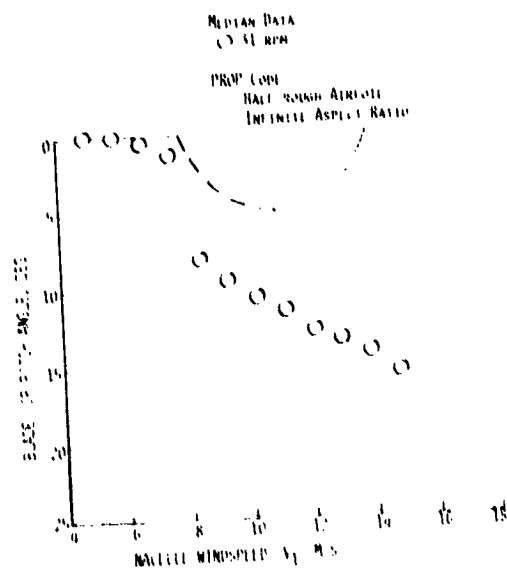


Figure 9 - Comparison of measured and calculated tip angle versus windspeed using classical theory for the Mod-0 steel spar, tip control blades

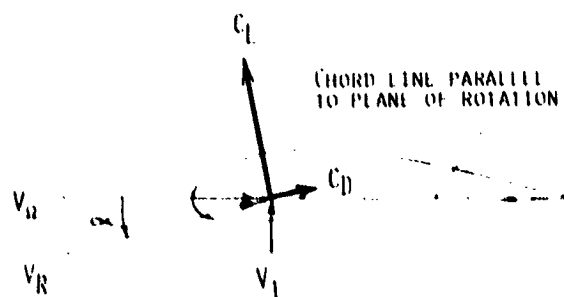


Figure 11 - Blade element wind velocity and force vector diagram

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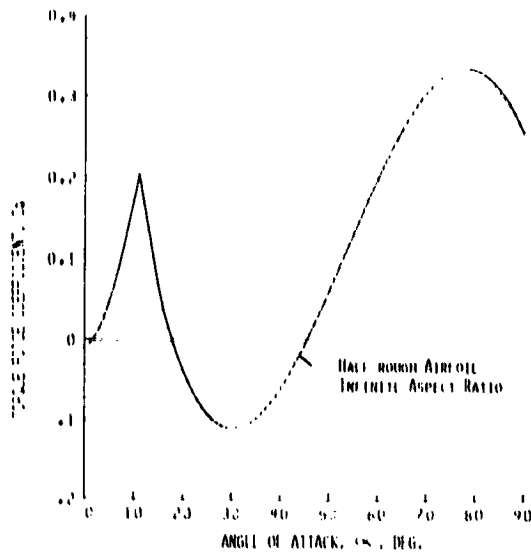


Figure 12 - Aerodynamic torque force coefficient versus angle of attack for "half-rough" NACA 23018 airfoil

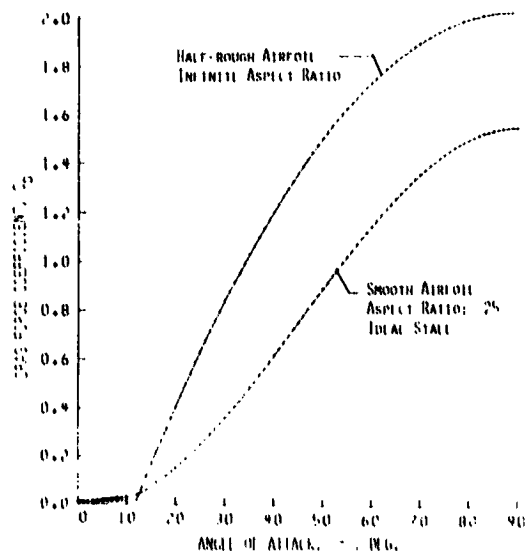
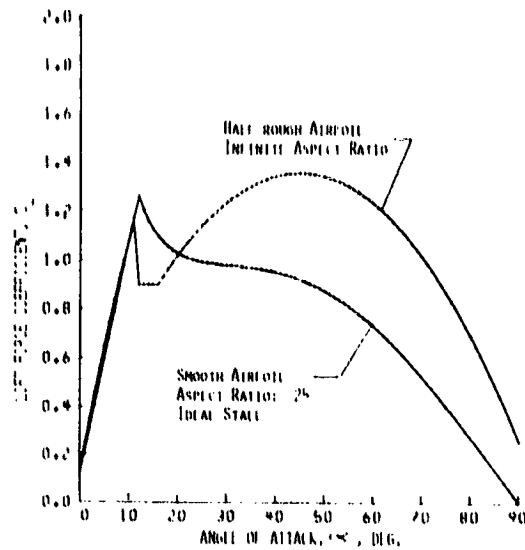


Figure 14 - Comparison of two dimensional "half-rough" and improved aerodynamic data

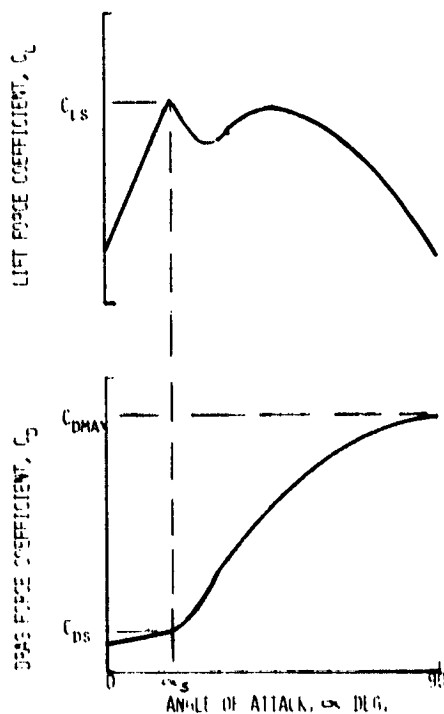


Figure 13 - General aerodynamic characteristics for idealized stall model

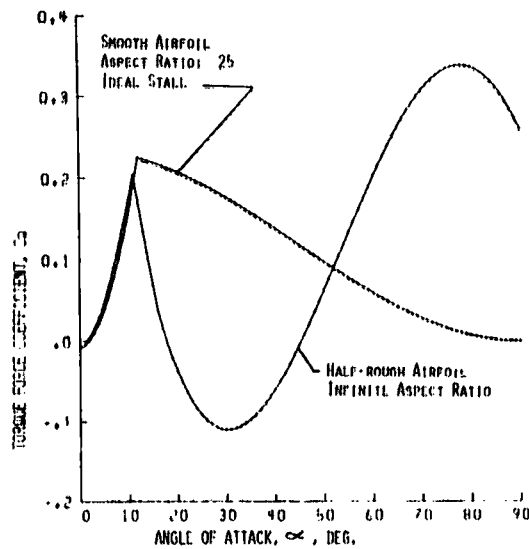


Figure 15 - Comparison of two dimensional "half-rough" and improved aerodynamic torque force coefficient

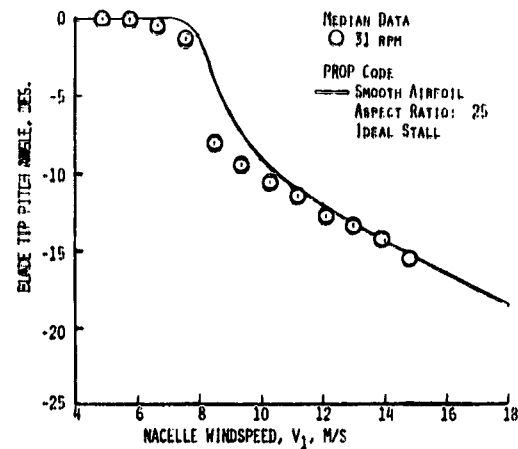


Figure 17 - Comparison of measured and calculated tip angle versus windspeed using improved aerodynamic data for the Mod-0 steel spar blades

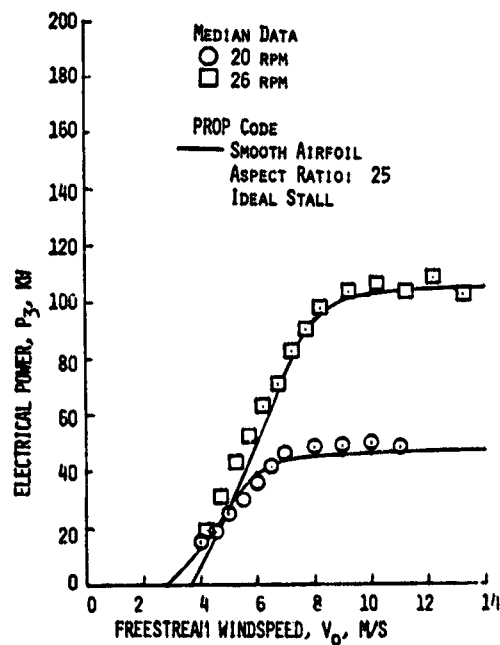


Figure 16 - Comparison of measured and calculated performance using improved aerodynamic data for the Mod-0 aluminum blades

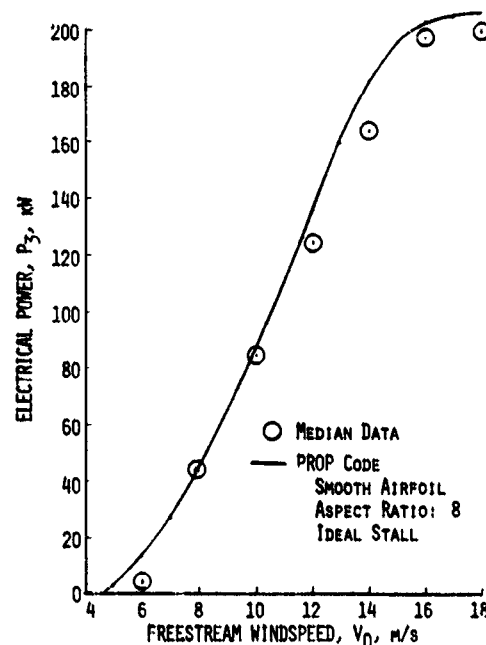


Figure 18 - Comparison of measured and calculated performance using improved aerodynamics for the Danish Gedser wind turbines

## QUESTIONS AND ANSWERS

L. Viterna

From: B. Dahlroth

Q: Comment on the effect of dynamic stall.

A: *We did not observe any significant effects of dynamic stall even though the 230XX series airfoil were used on the MOD-0. System dynamic loads were well behaved during these tests.*

From: J. Dugundji

Q: How did you keep the turbine at constant RPM throughout the wind speed range? How do you keep it from overspeeding?

A: *The electrical generator is held at a near synchronous speed with respect to the electrical line. The actual rotor speed deviates from the nominal RPM due to slip i.e. the fluid coupling in the drive train. A high speed shaft brake was available to prevent overspeed in an emergency upon loss of electrical load.*

From: Anonymous

Q: If the peak power is more than doubled by going from 20-26 RPM, what is the power limit from increasing RPM?

A: *There is no practical aerodynamic limit to maximum power with increasing RPM. At higher rotor speeds the rotor stalls at a higher windspeed and thus a much higher power.*

From: M. Rolland

Q: How would you characterize the starting ability of the fixed pitch rotor? Is there a sacrifice with fixed pitch?

A: *This is not addressed in the presentation. We have studied starting characteristics of fixed pitch rotors and believe it is possible to design a fixed pitch machine which will start in low winds and not be penalized significantly in performance. The zero twist blades on MOD-0 start with about 4 degrees of pitch in a 5 m/s wind. The 34 degree twisted blades start with 0 degrees of pitch in a similar wind.*

From: K. Foreman

Q: How do you explain the revised aero-characteristics of the blade after stall, also Reynolds number effects?

A: *We believe this is due to three-dimensional flow effects which are not accounted for using the classical blade element-momentum theory. The airfoil data is modeled at the Reynolds number at the 75 percent span of the blade.*

L. Viterna (continued)

From: G. R. Ketley

Q: Do you have any experience of the effect on the stalled power curve of the smooth surface-laminar flow aerofoils, instead of the half-rough 23XXX series?

A: *Performance data for a NACA 643-618 airfoil is being reduced. Some results are given in John Glasgow's paper, "Stall-Induced Instability of a Tilted Rotor."*

## STALL INDUCED INSTABILITY OF A TEETERED ROTOR

John C. Glasgow and Robert D. Corrigan

National Aeronautics & Space Administration  
Lewis Research Center  
Cleveland, Ohio

## ABSTRACT

Recent tests on the 38m Mod-0 horizontal axis experimental wind turbine have yielded quantitative information on stall induced instability of a teetered rotor. Tests were conducted on rotor blades with NACA 230 series and NACA 643-618 airfoils at low rotor speeds to produce high angles of attack at relatively low wind speeds and power levels. The behavior of the rotor shows good agreement with predicted rotor response based on blade angle of attack calculations and airfoil section properties. The untwisted blades with the 64 series airfoil sections had a slower rate of onset of rotor instability when compared with the twisted 230 series blades, but high teeter angles and teeter stop impacts were experienced with both rotors as wind speeds increased to produce high angles of attack on the outboard portion of the blade. The relative importance of blade twist and airfoil section stall characteristics on the rate of onset of rotor instability with increasing wind speed was not established however. Blade pitch was shown to be effective in eliminating rotor instability at the expense of some loss in rotor performance near rated wind speed.

## INTRODUCTION

The latest large horizontal axis wind turbine designs in the U. S. have shown a definite preference for two-bladed, teetered rotors. This design choice is influenced largely by the cost of wind turbine blades and the reduced loads afforded by a teetered rotor on a two-bladed machine. Both the 2.5 MW Mod-2 wind turbine, recently installed at Goodnoe Hills, Washington and the 4 MW WTS-4/SVU wind turbine, under construction at Medicine Bow, Wyoming have two-bladed, teetered rotors. In support of these programs, tests have been conducted of the Mod-0 100 kW Experimental wind turbine to provide information on operational characteristics of two-bladed teetered rotors and results were presented in References 1 and 2.

Concern was expressed early in the design of teetered rotors about the amplitude of teeter motion which affects tower clearance, Coriolis forces in the drive train, and the design of teeter motion stops. Initial tests on the Mod-0 indicated teeter motions in excess of  $\pm 6$  degrees could be expected in gusty wind conditions [1]. As more operational experience was gained, it became obvious that the large amplitude teeter motions were connected with a reduced rotor stability margin which occurs as the rotor operates near rated wind speed [2], where high local angles of attack occur on the outboard portion of the rotor blade. Subsequent to this discovery, tests were conducted on the Mod-0 wind turbine to more clearly define the effect of stall on a teetered rotor stability. The results of these tests are the subject of this report.

## TEST CONFIGURATION

The teetered rotor stall tests were conducted on the Mod-0 100 kW experimental wind turbine shown schematically in Figure 1. The essential features of the machine are described in References 1 and 2. All tests were conducted in the downwind rotor configuration, i.e., with the rotor downwind of the supporting tower. Two rotor configurations were tested, a fixed pitch rotor with highly twisted aluminum blades and a tip-controlled rotor with steel spar blades having no twist. Both rotors were uncone and used the same teetered hub. The blades are described in the rotor section.

Wind speed was measured at hub height on an anemometer 1.56 rotor diameters upwind of the wind turbine tower. (Wind data are currently being taken at the Mod-0 test site on an array of five measuring stations at hub height, at a radial distance of 59.4m (195 ft.) from the tower centerline and spaced at 45 degree intervals covering the directions of the most prevalent winds. The measuring station most nearly upwind during a test is selected as the reference wind speed.) Wind turbine orientation relative to the wind is determined by the anemometer/wind vane mounted on the nacelle.

The tests were conducted at nominal rotor speeds of 20 and 26 rpm; however, actual rotor speeds were somewhat higher due to slip in the drive train, and more precise rotor speed is presented in the text below. The drive train was changed during the test, with the tests of the fixed pitch aluminum blades being conducted with a synchronous generator and a fluid coupling (for slip) in the drive train, and the steel spar blade test being conducted with a high-slip, 2-speed induction generator and with the fluid coupling removed. Other than the slight change in rotor speed, it is felt that the drive train changes had no effect on the test results.

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## Rotor

Two rotors were tested for the effect of stall on teetered rotor instability. The first series of tests was run with aluminum blades which employ the NACA 230 series airfoil and are highly twisted. Due to the constraints of the hub geometry, these blades had to be installed such that the chord plane at the 3/4 radius point made an angle of +2.8 degrees with the rotor plane (feathered is -90 deg.) which exacerbated the tendency to stall by creating high angles of attack at lower wind speeds. The second series of tests was conducted with a steel spar, tip-controlled blade with a high performance NACA 643-618 airfoil over the movable outboard 30% of the blade. This airfoil has very gentle stall properties, and the effect of this characteristic on stall was of particular interest in the study. The characteristics of the rotors are summarized in Table 1, blade planforms are shown in Figures 2 and 3, and blade thickness and twist distribution for the aluminum blades are presented in Figures 4 and 5.

Table 1 - ROTOR CHARACTERISTICS

Steel Spar, Tip Control Blade	Twisted Aluminum Blade
Rotor dia., m (ft). . 38.39 (126.0)	Rotor dia., m (ft). 38.5 (126.37)
Root cutout, % span . . . . . 23	Root Cutout, % Span . . . . . 5
Tip control, % span . . . . . 30	Fixed Pitch . . . . . --
Blade pitch, inb'd sec., deg. Zero	Blade Pitch 75% Span, deg. . 2.8
Airfoil (inb'd sect.) . NACA 23024	Airfoil . . . . . NACA 230 series
(outb'd 30%). NACA 643-618	(root to tip)
Taper. . . . . Linear	Taper . . . . . Linear
Twist, deg. . . . . Zero	Twist, deg. . . . . 34
Solidity. . . . . 0.033	Solidity. . . . . 0.030
Precone, deg. . . . . Zero	Precone, deg. . . . . Zero
Max. teeter motion, deg. . . . . +6	Max teeter motion, deg. . . . . +6
Blade mass, kg (lb) . . 1815 (4000)	Blade mass, kg (lb) . 1043 (2300)
Blade Lock number*. . . . . 6.56	Blade Lock number*. . . . . 11.95

\* Blade Lock number,  $\gamma$ , is the ratio of aerodynamic force to inertia force on a rotor blade and is defined as:

$$\gamma = \frac{\rho a_0 c R^4}{I_B}$$



where

$\rho$  = air density

$a_0$  = slope of airfoil lift curve

$c$  = average blade chord

$R$  = blade radius at tip

$I_B$  = blade mass moment of inertia

## TEST RESULTS

Tests were conducted on the wind turbine at low rotor speeds to reduce the wind speed and power at which blade stall was predicted to occur and at two rotor speeds on the fixed pitch rotor to demonstrate any effects which might occur due to increased rotor speed. Results are presented for the tip-controlled rotor in two modes of operation, first with the blade pitch fixed at zero degrees; and second, in the power control mode with the maximum power set at 90 kW.

The test results are presented in terms of power and teeter angle versus wind speed. Data presented were obtained from a Bins analysis [3] of data taken during wind turbine operation. The median values of alternator power output, and the median and maximum values of each bin of the cyclic teeter angle are shown in Figures 6 to 9. It appears from the test results that the median value of teeter angle is indicative of the behavior of the rotor in steady winds while the maximum value of teeter angle is indicative of the stall margin or the behavior of the rotor in unsteady winds. A decrease in stall margin is indicated by an increase in maximum teeter angle. The results are discussed in detail in the Discussion section below.

Tests were conducted at nominal rotor speeds of 20 and 26 rpm; however, due to various levels of slip in the drive train, slight variations in rotor speed occurred from these nominal values. Rotor speeds at zero power level and at a power level of 100 kW along with the slip at 100 kW as a percent of the zero power rotor speed are given in the table below. Drive train slip has been found to vary linearly with power over the normal range of power levels for both the synchronous generator and fluid coupling drive train and for the rigid drive train with the high-slip induction generator. Rotor speeds and values of slip for each test configuration are presented in Table 2 below.

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Table 2 - Rotor Speed and Drive Train Slip for Configurations Tested

Configuration and Nominal Rotor Speed	Rotor Speed - rpm		Drive Train Slip %
	0 Power	100 kW	
Aluminum Blades - 20 rpm	20.0	21.4	7.2
Aluminum Blades - 26 rpm	26.3	27.5	4.6
Steel Spar Blade 20 rpm Fixed Pitch Mode	19.9	20.8	4.5
Steel Spar Blade 20 rpm Power Control Mode	20.7	22.2	7.2

We feel that the rotor speed changes due to changes in the drive train have no effect on the general conclusions of this work and therefore the nominal values of rotor speed are used in the data presented below.

Results for the twisted aluminum blades with the NACA 230 series airfoil and for the steel spar, tip-controlled blade with the high performance NACA 643-618 airfoil are presented below.

Twisted Aluminum Blades

Figure 6 presents power and teeter angle versus wind speed for the 230 series airfoil at 20 rpm. The power curve indicates that rotor stall begins to occur at a wind speed somewhere between 4.5 and 5.5 m/s and that stall is well established by 7 m/s. The plot of teeter angle indicates similar relationships with wind speed, with the median value of teeter angle starting to increase from a base value of 1.25 degrees at about 5 m/s and total stall occurring at 7 m/s. The maximum value of teeter angle indicates a similar trend with unstalled operation indicated below 3.5 or 4 m/s and fully stalled operation occurring above 6 m/s.

Operation of the twisted aluminum blades at 26 rpm, shown in Figure 7, produced results similar to operation at 20 rpm except that the effects of stall are seen at a wind speed about 2 m/s higher. The power versus wind speed curve shows unstalled operation at wind speeds below 6.5 m/s, the onset of stall at about 7.5 m/s and a fully stalled rotor at 8.5 to 9 m/s. The plot of teeter angle versus wind speed would indicate similar conclusions, particularly when only the median values of teeter angle are considered. Using the maximum values of teeter angle as the stall criterion would reduce the wind speeds for stalled and unstalled rotor operation slightly, however.

### Tip Controlled Rotor with High Performance Tips

Figures 8 and 9 present output power and teeter angle data for the tip-controlled rotor with the NACA 643-618 high performance airfoil on the moveable tip which extends from the 70% span point to the tip. This airfoil was of particular interest in these tests because of its gentle stall characteristics compared to the NACA 230 series airfoil which loses lift abruptly as the stall angle is exceeded. Section lift characteristics for the airfoils tested are shown in Figure 10. The section lift characteristics are derived from Reference 5 and represent values for a "one-half rough" surface [6] on the outboard section of the rotor blade.

The power versus wind speed curve of Figure 8a indicates this gentle stall characteristic but it is demonstrated more vividly in the teeter angle versus wind speed plot, Figure 8b. Although the maximum values of teeter angle indicates behavior similar to that obtained for the rotor with the NACA 230 series airfoil the median values of teeter angle show a much gentler increase of teeter angle with wind speed. To determine the state of the rotor we must rely on the maximum teeter angle rather than the power curve or the median value of teeter angle since maximum values indicate incidence of extreme motion. Using the maximum teeter angle as the criterion, unstalled operation is apparent at wind speeds below 5 m/s, stall onset occurs between 5 and 6 m/s and the rotor is fully stalled, at wind speeds above 6.5 m/s.

Tests of the tip-controlled rotor were run with the maximum power set at 90 kW, referred to as the Power Control mode in Table 2. These results were of interest because they show the effect of power control on rotor teeter stability. As power control becomes effective, the blades are pitched toward feather which reduces the angle of attack. When the blade angle of attack is low enough to unstall the blades, teeter stability is reestablished. These effects are indicated in the results presented in Figure 9. The power versus wind speed plot, Figure 9a, is linear with wind speed and shows no tendency to flatten as wind speed increases, over the wind speed range of the test. The teeter angle plot, however, indicates major differences when compared with the fixed pitch case shown in Figure 8. The median value of teeter angle increases with wind speed until a wind speed of 8 m/s is reached where the teeter angle decreases as power control becomes effective and starts to reduce blade pitch angle to maintain the power set point. The effect of power control is also seen in the maximum value of teeter angle where the data indicates that impact with the teeter stops did not occur at wind speeds in excess of 11 m/s showing the effect of blade pitch angle in reducing the angle of attack on the tip section and reestablishing rotor stability.

A comparison of the teeter angles for fixed pitch operation, Figure 8b, with those of the power control mode of operation, Figure 9b, will show that teeter angles for wind speeds below 8 m/s are higher for the power control mode of operation. No explanation can be given for this difference at this time. Both rotors are operating in the fixed-pitch, full power position at those wind speeds and all other machine parameters with the exception of a small change in rotor speed, were the same. The difference could arise from a difference in the character of the wind for the two tests. Each test was run for a period of approximately 3 hours on different days and turbulence or shear in the wind could affect the results. Regardless of the differences in the details, the general relationships and information obtained are felt to be valid.

## DISCUSSION

The test data indicates graphically the effect of blade stall on the stability of teetered rotors. The fact that nearly identical teeter response occurs on the fixed pitch rotor with twisted aluminum blades at 20 and 26 rpm but at 2 m/s higher in wind speed indicates that the rotor instability observed is strongly related to the local angle of attack on the outboard portion of the blade. Figure 11 shows calculated values of angle of attack versus wind speed for 20 and 26 rpm, at 0.7 and 0.9 span for the twisted aluminum blade, obtained from the PROP code [4]. Figure 12 shows similar data for the tip controlled rotor operating at a fixed pitch angle of zero degrees. Figure 11 shows a 2 m/s difference between 20 and 26 rpm for the same local angle of attack. It is also of interest to note that with the highly twisted blades, see Figure 11, the 0.7 and 0.9 blade stations are predicted to have approximately equal angles of attack near the stall point of 14 degrees. This could explain the abrupt nature of the stall indicated by the median teeter angle values in Figures 6b and 7b, as well as the sharp stall characteristics of the NACA 230 series airfoils shown in Figure 10. Indeed, the fact that the twisted blades tested are predicted to stall over the outboard 30% of the blade at the same wind speed may be the most important factor in the behavior of the fixed pitch rotor. Tests are planned with untwisted blades and the NACA 230 series airfoil which may shed more light on the relative importance of twist and airfoil two-dimensional stall characteristics on teetered rotor stability.

The untwisted blades of the tip-controlled rotor, see Figure 12, experience a calculated angle of attack difference of 2 degrees or more from the 0.7 to the 0.9 blade station which could have some effect on the behavior of teeter angles as wind speed increases, as well as the benign stall characteristic of the NACA 64 series airfoil. Unfortunately the configurations tested did not eliminate this variable from the data.

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If the wind speed is obtained for a given rotor condition, i.e., stable or unstable, from Figures 6b, 7b, and 8b, an approximate angle of attack for each condition for the blade tip can be obtained from Figures 11 and 12 which present calculated angles of attack versus wind speed for each rotor. This process has been followed and the results are presented in Table 3 below.

Table 3 - CALCULATED ANGLES OF ATTACK FOR STABLE AND UNSTABLE ROTORS  
(Average values for Outboard 30% of Blade)

Rotor Configuration	Stable		Unstable	
	Wind Speed	Angle of Attack	Wind Speed	Angle of Attack
	m/s	deg.	m/s	deg.
230 Series, 20 rpm	4	8.5	6+	13.5
230 Series, 26 rpm	6	9.5	8+	13.5
64 Series, 20 rpm	5	6.5	6.5	9.5

Airfoil section lift properties for the two rotors, derived from Reference 5, are shown in Figure 10. Locating the calculated angles of attack for stalled and unstalled operation on the section lift curves, shows that the calculated angle of attacks and the section lift curves give a good indication of rotor stability for both the NACA 230 series and for the NACA 643-618 rotors. In the case of both airfoils, a stable rotor is indicated when the angle of attack is along the linear portion of the section lift curve and a stalled rotor is indicated by an angle of attack which is high enough to place the blade on the non-linear portion of the curve. Also, the results indicate that a rather straightforward calculation of blade angle of attack will show where teetered rotor stall can be expected. Operation on the non-linear portion of the lift curve reduces damping which makes the teetered rotor lose stability margin. This makes it subject to high amplitude teeter motions in variable winds.

The results from the teeter angle response tests indicate the need to pitch the blades toward feather as the blade local angle of attack approaches the non-linear portion of the section lift curve. In cases where rotors operate at high blade angles of attack, this action would provide a stall margin and prevent excessive teeter motion. This approach would reduce the performance of the rotor near rated wind speed somewhat, but would reduce the chance of impacting the teeter stops which would improve the reliability and life of the rotor.

## CONCLUSIONS

Tests conducted on the 100 kW Mod-0 experimental wind turbine have demonstrated the causes and effects of stall induced teetered rotor instability. As a result of the experiments performed the conclusions listed below were derived.

- o Rotor stall which produces teetered rotor instability occurs when the angle of attack on the outboard 30% of the rotor blade approaches the non-linear portion of the section lift curve of the airfoil.
- o Tests at two rotor speeds indicated that rotor speed had no influence on stall. The same effects were noted at approximately the same tip speed ratio, i.e., at a higher wind speed for the higher rpm case.
- o Blade angle of attack calculations made with relatively straightforward aerodynamic techniques and airfoil section lift properties appear to explain fully the basic elements of stall induced teetered rotor instability.
- o Blade pitch can be used to provide a stability margin which will prevent or reduce the tendency of rotors to become unstable near rated wind speed. This will result in a slight loss of rotor performance however.
- o The relative importance of blade twist and of airfoil section stall characteristics on the rate of onset of rotor instability with increasing wind speed was not established by these tests. Tests are planned which will provide this information.

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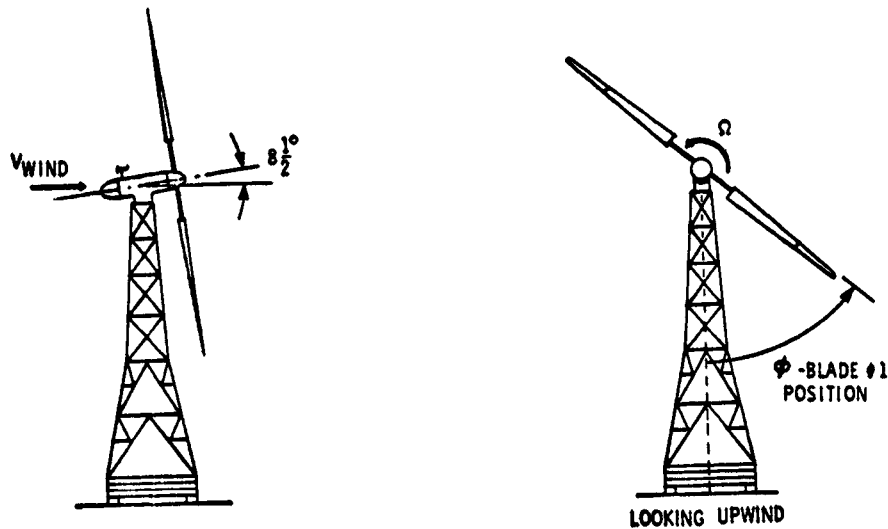


Figure 1. - Mod-0 100 kW Experimental Wind Turbine with Teetered, Tip-Controlled Rotor.

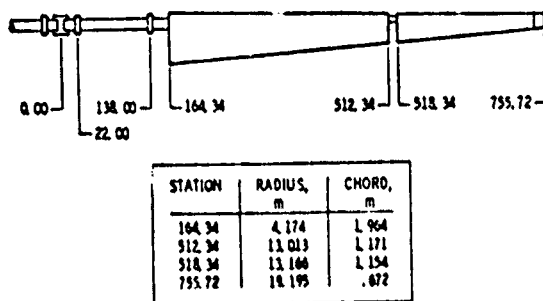


Figure 2. Steel Spar, Tip Control Blade Planform

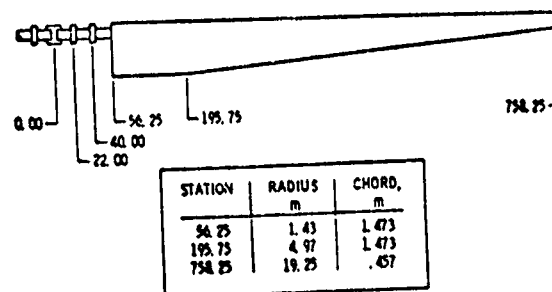


Figure 3. Twisted Aluminum Blade Planform

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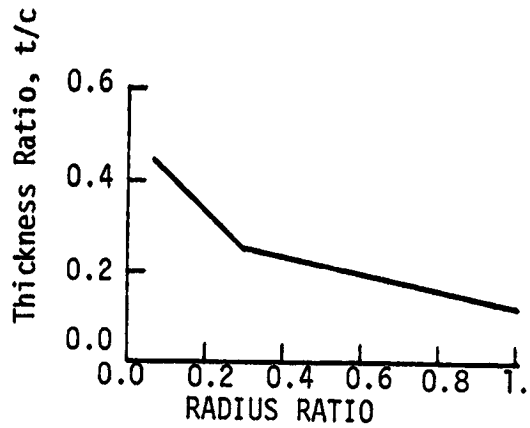


Figure 4. Thickness to Chord Ratio for Twisted Aluminum Blade

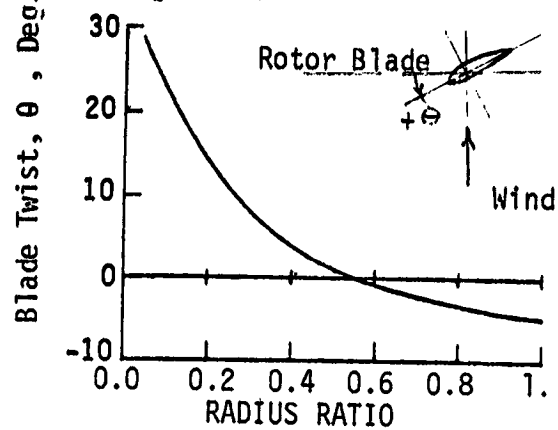
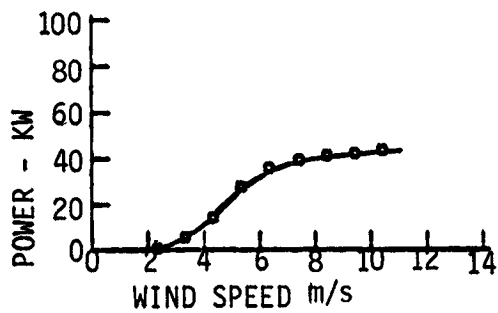
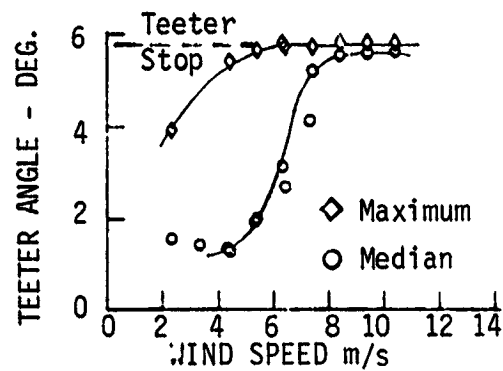


Figure 5. Twist Distribution for Twisted Aluminum Blades



(a) Alternator Power

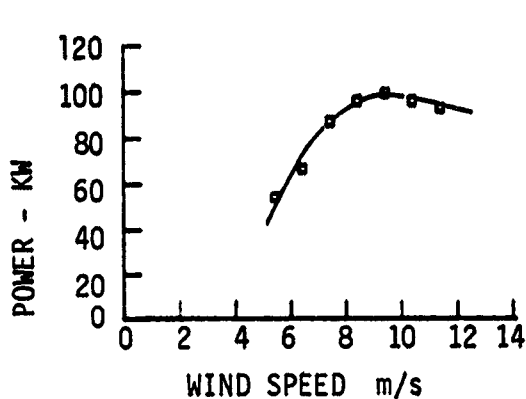


(b) Cyclic Teeter Angle

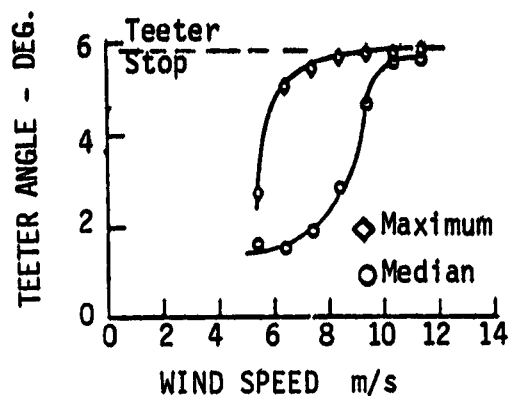
Figure 6. Fixed Pitch Rotor with NACA 230 Series Twisted Aluminum Blades at 20 rpm; (a) Alternator Power Output, and (b) Cyclic Teeter Angle Versus Wind Speed



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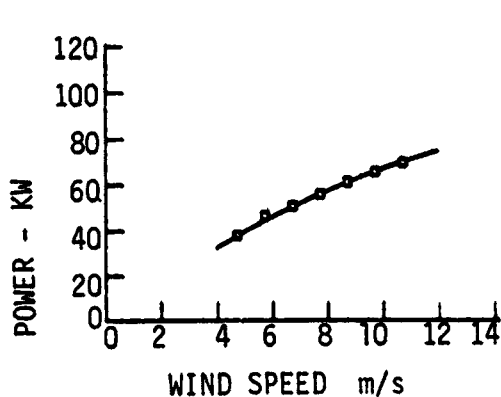


(a) Alternator Power

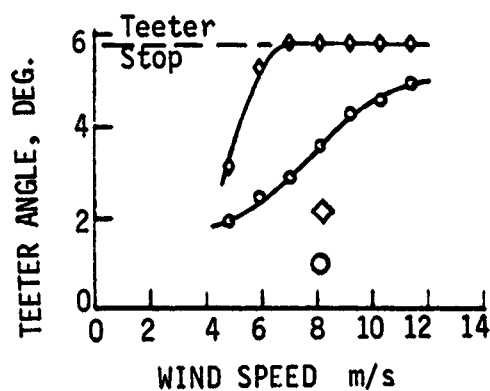


(b) Cyclic Teeter Angle

Figure 7. Fixed Pitch Rotor with NACA 230 Series Twisted Aluminum Blades at 26 rpm; (a) Alternator Power Output and (b) Cyclic Teeter Angle versus Wind Speed



(a) Alternator Power



(b) Cyclic Teeter Angle

Figure 8. Tip-Controlled Rotor with NACA 64<sub>3</sub>-618 Moveable Tip in Fixed Pitch Mode at 20 rpm; (a) Alternator Power Output and (b) Cyclic Teeter Angle Versus Wind Speed

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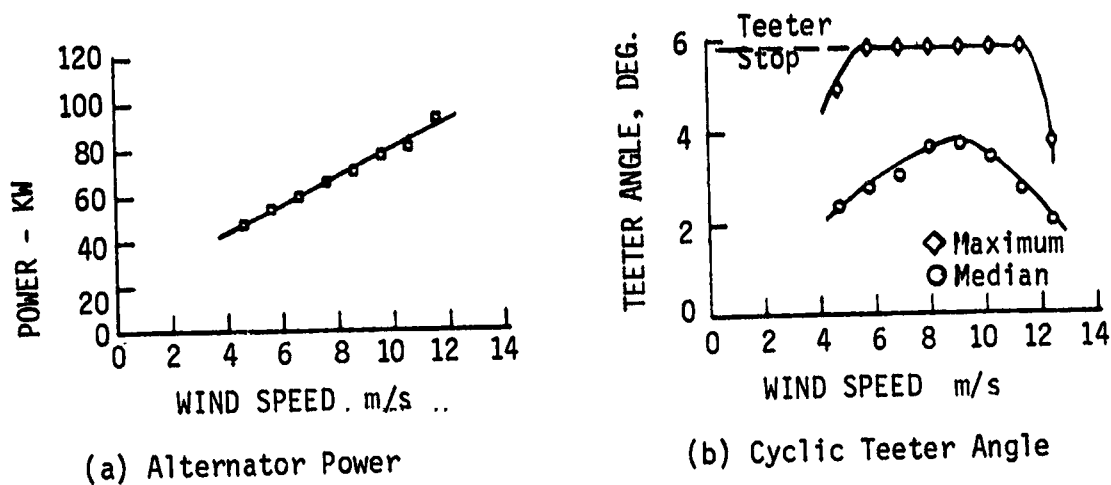


Figure 9. Tip-Controlled Rotor with NACA 64<sub>3</sub>-618 Moveable Tips in Power Control Mode at 20 rpm; (a) Alternator Power Output and (b) Cyclic Teeter Angle versus Wind Speed

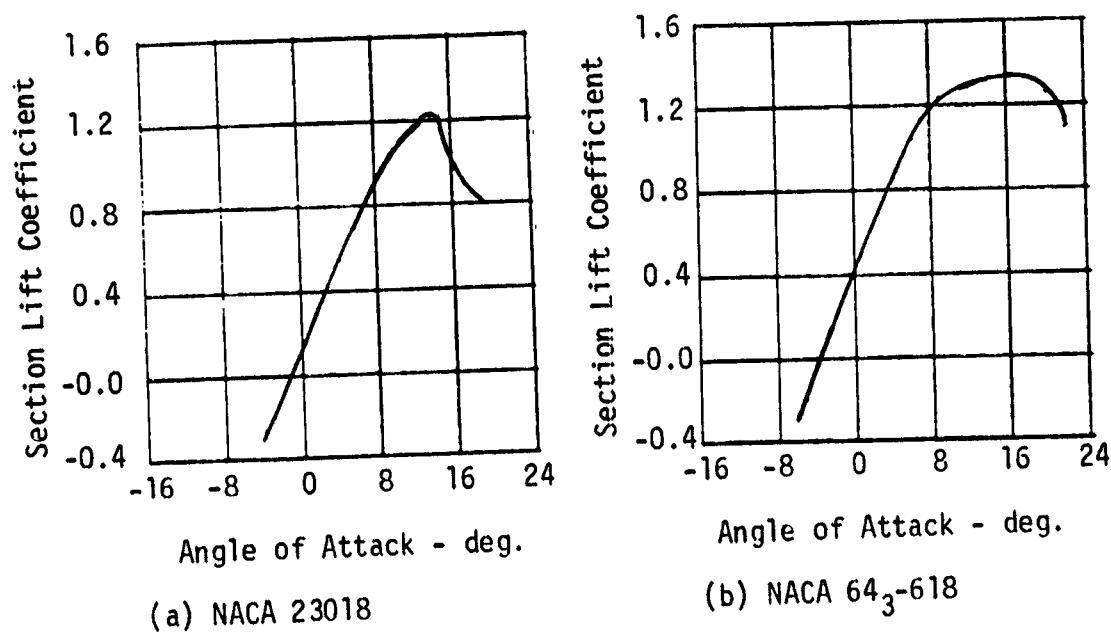


Figure 10. Section Lift Characteristics for (a) NACA 23018 and (b) NACA 64<sub>3</sub>-618 Airfoils. From Abbott, van Doenhoff, and Stivers [5], ("half rough")

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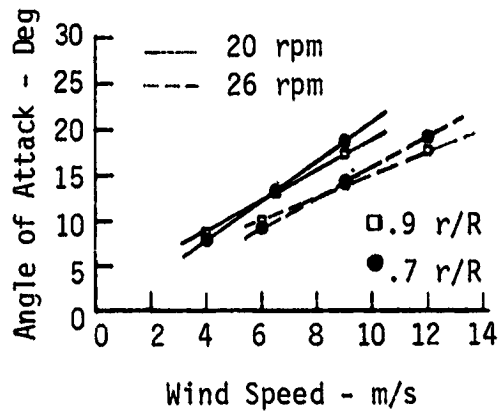


Figure 11. Calculated Blade Angle of Attack Versus Wind Speed for Twisted Aluminum Blade at 0.7 and 0.9 Blade Span for Two Rotor Speeds 20 and 26 rpm

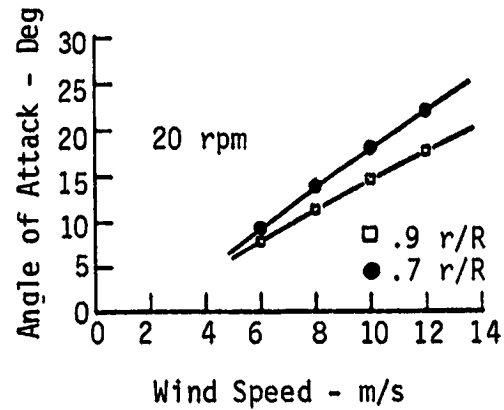


Figure 12. Calculated Blade Angle of Attack Versus Wind Speed for Tip-Controlled Blade, for Blade Pitch Angle of 0 Deg., at 0.7 and 0.9 Blade Span. Rotor Speed 20 rpm

QUESTIONS AND ANSWERS

J. C. Glasgow

From: M. Snyder

Q: If a design is one in which the stall limitation of power is expected for control, what measures can be taken with a teetered rotor to minimize the teeter instability?

A: *Some means must be provided to replace the aerodynamic damping which is lost as the blades stall. We plan to test a teetered hub which provides this type of damping with elastomeric material in the teeter stops. We also plan to limit the free travel which will make these stops effective at teeter angles near 1°.*

From: R. Barton

Q: How strongly did the 6° teeter stop setting influence the "stability" definition (i.e. as long as  $C_L/\alpha$  is not (-) a bigger deflection allowance should be stable)?

A: *This is not the case, a teetering rotor creates an individual angle of attack,  $\alpha$ , equal to the maximum teeter angle. As the teeter angle increases the tendency for the rotor to become unstable increases because the tip angle of attack increases and goes more deeply into stall.*

From: B. Dahlroth

Q: Do you see an increased variation in generator output at high teeter angles?

A: *Yes, this is due to the Coriolis forces associated with rotor teetering. These are proportional to the teeter velocity which is a function of the teeter amplitude. Drive train damping produced by fluid couplings, slip in induction generators, or damping in the gear box mounting will reduce the effects of these forces.*

From: B. Barron

Q: Are you considering installation of a dynamic stabilization mechanism into the teeter system?

A: *We are planning to install elastomeric teeter stops with about  $\pm 1^\circ$  of free teeter motion to evaluate the effect of this device in providing the damping lost when the blade stalls.*

From: L. P. Rowley

Q: Has the MOD-2 data confirmed the findings produced by the MOD-0 tests?

A: *I cannot respond to this question. I am not familiar with the details of the MOD-2 data.*

J. C. Glasgow (continued)

From: K. Foreman

Q: What are your estimates of the teeter stability characteristics for a 3-bladed instead of a 2-bladed turbine?

A: *I have no experience with a 3-bladed rotor. I do not believe teetering would offer much advantage to a 3-bladed machine since the rotor is polar symmetric.*

From: T. Andersen

Q: How closely was the yaw error controlled during the stall/teeter instability testing?

A: *The standard yaw control was used during these tests. This has a  $\pm 20^\circ$  dead band and corrects to  $\pm 10^\circ$  or better when the yaw motor is activated.*

From: D. Z. Bailey

Q: Did you see any evidence of dynamic stall,  $C_{L_s}$  higher than the static or moment increase?

A: *Yes, we have seen this in every test in which we have attempted to define the stall point for fixed pitch rotors. Rotor stall occurs at higher power levels than predicted by the 2D rotor power programs. More work is needed to gain an understanding of the aerodynamics of the horizontal axis wind turbine rotors.*

# FREE YAW PERFORMANCE OF THE MOD-0 LARGE HORIZONTAL AXIS 100 KW WIND TURBINE

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## ABSTRACT

The NASA Mod-0 Large Horizontal Axis 100 kW Wind Turbine was operated in free yaw with an unconed teetered, downwind rotor mounted on a nacelle having 8-1/20 tilt. Two series of tests were run, the first series with 19 meter twisted aluminum blades and the second series with 19 meter untwisted steel spar blades with tip control. Rotor speed were nominally 20, 26 and 31 rpm. It was found the nacelle stabilized in free yaw at a yaw angle of between -55° to -45°, was relatively independent of wind speed and was well damped to short term variations in wind direction. Power output of the wind turbine in free yaw, aligned at a large yaw angle, was considerably less than that if the wind turbine were aligned with the wind. For the Mod-0 wind turbine at 26 rpm, the MOSTAB computer code calculations of the free yaw alignment angle and power output compare reasonably well with experimental data. MOSTAB calculations indicate that elimination of tilt and adding coning will improve wind turbine alignment with the wind and that wind shear has a slight detrimental effect on the free yaw alignment angle.

## INTRODUCTION

Free yaw of a wind turbine has been a goal of designers for some time because of the attractiveness of eliminating the yaw drive. If a wind turbine in free yaw, aligns closely with the wind direction, power output can be maximized. Additionally, an active yaw control system is not required; which simplifies control systems and reduces mechanical components. Also, it is anticipated that during shutdown in high winds, the wind turbine could be placed in free yaw with one blade tip feathered. This configuration will cause it to weather vane, bringing the blades parallel to the wind and thus reducing blade and tower loads in high winds. To be practical, a wind turbine in free yaw must align itself closely with the wind in order to allow the rotor to capture the most energy from the wind. As expected, the

power output of a wind turbine in free yaw aligned at some large yaw angle off the wind should not produce as much power compared to the wind turbine in active yaw aligned with the wind.

Tests have been conducted by NASA on free yaw of the Mod-0 wind turbine. This intermediate report will present data on the operational characteristics of the NASA Mod-0 wind turbine in free yaw having a nacelle tilt of  $8.5^\circ$ ,  $0^\circ$  coning and a downwind rotor. Two blade configurations were used: (1) fixed pitch twisted aluminum blades at nominal rotor speeds of 20, 26, and 31 rpm, and (2) untwisted steel spar blades with tip control at a nominal rotor speed of 31 rpm. Operational characteristics to be presented are nacelle yaw alignment, nacelle yaw response, and power output. Experimental data for the twisted aluminum blades on nacelle yaw alignment were compared with MOSTAB computer program predictions, and MOSTAB calculations used to analyze the affects of nacelle tilt, blade coning and wind shear on Mod-0 wind turbine free yaw alignment angle.

#### EXPERIMENT DESCRIPTION

Free yaw tests were conducted on the NASA Mod-0 100 kW Experimental Wind Turbine, as described in References 1, 2 and 3. The wind turbine was configured with a teetered, downwind rotor. Two test series conducted, the first was with fixed pitch, twisted blades operated at nominal rotor speeds of 20, 26 and 31 rpm; and the second series with a tip-controlled blade having no twist operated at a nominal rotor speed of 31 rpm.

The Mod-0 wind turbine (Figure 1) is composed of a 31.5 meter truss tower supporting a nacelle (Figure 2) which houses the alternator, drive train assembly, yaw drive assembly and rotor assembly. In order to provide adequate clearance of the tower by the blades, the nacelle is mounted with its longitudinal axis tilted  $8.5^\circ$  to the horizon, rotor end elevated.

The yaw drive assembly shown in Figure 2 consists of a single hydraulic motor/gear reducer system connected through a clutch to the pinion and ring gears. For active yaw, the yaw control system was operated with the clutch engaged and the yaw brake pressurized to maintain a set nacelle yaw angle with respect to the wind. For free yaw, the yaw drive system was disengaged from the ring gear by the clutch and the yaw brake was deactivated, allowing the nacelle to move freely about the yaw axis. (The friction torque in yaw, with the yaw drive and yaw brake disengaged is estimated to be 1912 n-m based on a friction coefficient of .02, nacelle/rotor weight of 14215 Kg, and a bearing radius of .69 m.)

The rotor assembly consisted of a two bladed teetered hub with  $\pm 6.0^\circ$  of teeter motion and  $0^\circ$  coning. The first series of tests were conducted with fixed pitch, twisted aluminum blades described in Table 1 and Figures 3, 4, 5. The 19.25 meter blades

TABLE 1

## BLADE CHARACTERISTICS OF THE TWISTED ALUMINUM BLADES

Rotor dia., m (ft.)	38.5 (126.3')
Root cutout, % span	5
Fixed pitch	2.8
Blade pitch 75% span, deg	NACA 230 series
Airfoil (root to tip)	Linear
Taper	26.5
Twist, deg	0.30
Solidity	0.0
Precone, deg	+6
Max teeter motion, deg	104.3 (2300)
Blade mass, kg (lb.)	

TABLE 2

## BLADE CHARACTERISTICS OF THE STEEL SPAR, TIP CONTROLLED BLADES

Rotor dia., m (ft.)	38.39 (126.0)
Root cutout, % span	23
Tip control, % span	30
Blade pitch, inb'd sec., deg	Zero
Airfoil (inb'd sect.)	NACA 23024
(outb'd 30%)	NACA 643-618
Taper	Linear
Twist, deg	Zero
Solidity	0.033
Precone, deg	Zero
Max. teeter motion, deg	+6
Blade mass, kg (lb.)	1815 (4000)



have a NACA 230 series airfoil, 30° of twist and are mounted on the hub so as to have a pitch angle of +2.8° relative to the plane of rotation (-90° is feathered) at the .75 radius station (Figure 4). The second series of tests were conducted with untwisted steel spar, tip-controlled blades described in Table 2 and Figure 6. The 19.18 meter blades have a NACA 230 series airfoil over the inboard section and a NACA 64 series airfoil over the outboard 30%. The blade is mounted with the chord plane parallel to the plane of rotation and the tip section mounted so as to have a 0° pitch angle when parallel to the blade chord. The tips can be pitched +10° to -65°.

Meteorological data was taken using an array of meteorological towers 59.4 meter from the wind turbine and spaced 45° apart. For a given test, the wind data was taken from the tower most nearly upwind of the wind turbine. The sensors on the towers are mounted at the wind turbine hub height. The nacelle yaw angle shown in Figure 7, was taken as the difference between nacelle azimuth and wind azimuth taken from the performance array. Data collection and reduction was accomplished using the data system and analysis described in reference 4. Brush strip chart recordings was also used.

The Modular Stability-High Frequency Wind Energy System Version (MOSTAB-HFW) computer program, which calculates wind turbine loads and motions, was utilized to predict the wind turbine's free yaw alignment angle for comparison with experimental data. References 5, 6 and 7 describe in detail the development and use of MOSTAB-HFW. For this paper, the wind turbine with fixed pitch, twisted aluminum blades was modeled for use with the MOSTAB-HFW code as described in Appendix A. Calculations were made for various trim conditions in order to obtain a relationship between yaw torque and yaw angle, for wind speeds of 5, 7 and 9 m/s. This data was then used for the yaw angle predictions. MOSTAB calculations were then made to determine the effects of nacelle tilt, rotor coning and wind shear on the free yaw alignment of the Mod-0 wind turbine.

## RESULTS

Free yaw data was collected on the rotor operating with: fixed pitch twisted aluminum blades at nominal rotor speeds of 20, 26 and 31 rpm in wind speeds of 4 to 10 m/s; and with tip-controlled steel spar blades at a rotor speed of 31 rpm in wind speeds of 4-10 m/s. The tests were designed to define wind turbine stability and performance in free yaw. Specifically, the data analysis determined the free yaw alignment angle, nacelle response to wind speed and direction changes and alternator power.

Analysis of the test data was accomplished by the use of the Bins analysis techniques (Ref. 4).

The nacelle's tilt of 8-1/2° plays an important part in the wind turbine's free yaw alignment angle. The 8-1/2° tilt introduces a

torque component from the rotor torque in the yaw axis. Because of the blade rotational direction and the fact the rotor is producing a torque, this torque component tends to yaw the machine in the minus yaw direction. This causes the wind turbine to align itself further away from the wind direction than if there were no tilt.

### Twisted Aluminum Blades

Measured data for nacelle yaw alignment of the wind turbine in free yaw with fixed pitch twisted aluminum blades is shown in Figures 8, 9 and 10 for rotor speeds of 20, 26, and 31 rpm. The figures describe wind turbine's yaw angle, or alignment relative to the wind, wind speed distribution and yaw angle distribution when stabilized in free yaw alignment. Shown in figures 8(a), 9(a) and 10(a) for the three rotor speeds, the nacelle's yaw angle is relatively constant and independent of the wind speed. The difference in free yaw operations for the three rotor speeds is the free yaw alignment angle. This is seen from the yaw angle distribution in figures 8(b), 9(b) and 10(b) which indicates that the modal (most occurring) yaw angle of the wind turbine at 20 rpm is  $-46.2^\circ$ , 26 rpm is  $-53.6^\circ$  and 31 rpm is  $-45.4^\circ$  off the wind.

The directional response of the Mod-0 wind turbine with fixed pitch, twisted aluminum blades was very stable and well damped in free yaw. The characteristics were similar for the three rotor speeds of 20, 26 and 31 rpm. Because of the similarity in directional response at the various speeds only 26 rpm rotor speed data is presented in figures 11 and 12.

These figures are segments of strip chart recordings of the nacelle azimuth, nacelle wind speed and nacelle yaw angle. The nacelle wind speed and yaw angle are measured by an anemometer/wind vane mounted 3.4 meters above the nacelle and 4.6 meters upwind of the rotor. Special care should be taken in directly using the nacelle wind speed and nacelle yaw angle in these recordings because the sensor readings of the nacelle mounted anemometer/wind vane may differ from the undisturbed wind speed and direction due to aerodynamic effects of the nacelle and rotor. As described before, the nacelle azimuth is the absolute angle of the nacelle with respect to the earth and the yaw angle is the difference between nacelle azimuth and the wind direction. The nacelle azimuth signal shows the motion of the nacelle with respect to the earth. Since the nacelle motion is generally steady, any short term fluctuations in the yaw angle signal are due mainly to wind direction variations.

Figure 11 shows the yaw response of the wind turbine operating at 26 rpm. In this case the nacelle was in active yaw aligned with the wind and then placed in free yaw. The nacelle yaw angle indicates that the nacelle yaw angle asymptotically approaches the free yaw alignment angle, with the yawing rate dependent upon the angular separation of the nacelle direction to its free yaw alignment angle and decaying to 0 as the free yaw alignment was approached. It should be noted that the nacelle's motion, as shown by nacelle

azimuth, in reaching free yaw alignment was smooth, gentle and without overshoot, indicating that the damping in yaw is very high. With a wind speed of 4 m/s, the nacelle had a 2/3 time constant (time to achieve 2/3 of the difference between an initial condition and final condition, used to describe asymptotic type situation) of approximately 30 seconds to travel from 0° yaw angle to -36° yaw angle; based on free yaw alignment of -54° yaw angle.

Once free yaw alignment has been established, nacelle yaw response to short term variations ( $\pm 10^\circ$  in 10 seconds) wind direction appears well damped and stable at the three rotor speeds tested. This can be seen in figure 12 by comparing the nacelle azimuth behavior to the nacelle yaw angle behavior. Nacelle yaw angle signal shows that short term variations of  $\pm 10^\circ$  or more, due to variations in wind direction, have little affect on the nacelle's motion relative to the earth.

Alternator power output for the wind turbine with twisted blades at free yaw alignment was recorded for rotor speeds of 20, 26 and 31 rpm and in wind speeds of 4 to 8 m/s. The power generating system consisted of a synchronous generator set up as shown in figure 2. For all three rotor speeds, the alternator power for the wind turbine, stabilized in free yaw, was between 30% - 50% of the alternator power for the same configuration aligned with the wind. No general relationship between power loss and yaw angle could be determined that was consistent with the data for all three rotor speeds. Since wind turbine operations at these poor efficiencies is not practical, only one power curve, typical of the three rotor speeds is shown. Figure 13 compares the power output versus wind speed, of the wind turbine at 20 rpm in active yaw aligned with the wind and in free yaw. Table 3 is a tabulation of points off the figure for the prevalent wind speeds.

TABLE 3 - WIND TURBINE PERFORMANCE - FREE YAW VS. ACTIVE YAW  
INTO WIND-TWISTED ALUMINUM BLADES - 20 RPM

REF. WIND SPEED (m/s)	AT POWER- FREE YAW (kW)	YAW ANGLE- FREE YAW (DEG.)	ALT. POWER ACTIVE YAW (kW)
4	6.5	-45	15.0
5	14.0	-46	28.0
6	19.5	-46	35.0

#### Steel Spar Blades with Tip Control

Nacelle yaw alignment for the wind turbine in free yaw having untwisted steel spar blades with tip control is shown in figure 14 for a rotor speed of 31 rpm. The data was collected with the Mod-0

wind turbine stabilized in free yaw and depict a free yaw alignment angle. The nacelle yaw angle versus reference wind speed and wind speed distribution shown in figure 14(a), is similar in nature to the free yaw data taken for the fixed pitch twisted aluminum blades, and shows a fairly constant yaw angle which is relatively independent of the wind speed for the wind speed range of 4-14 m/s. Figure 14(b) depicts the probability density of the nacelle yaw angles and indicates the wind turbine stabilized in free yaw with steel spar blades, and tip control has a modal yaw angle of  $-46.50^\circ$ .

The nacelle directional responses for the wind turbine in free yaw with the untwisted steel spar blades with tip control and at 31 rpm are shown in figures 15 and 16. As stated earlier, care should be taken in directly using the nacelle wind speed and nacelle yaw angle shown on these strip charts because of the possible nacelle/rotor interference. The nacelle was placed in free yaw at approximately  $-35^\circ$  yaw angle and shows the tendency to reach and stabilize at the free yaw alignment angle. Unlike the rotor with twisted aluminum blades, the nacelle's motion as shown by the nacelle's azimuth is not clearly asymptotic nor as well damped. The "low dampened" yaw motion of the nacelle continues to occur at a "stabilized" nacelle free yaw alignment as shown in figure 16 where the wind turbine has been in free yaw for a long period of time ( 20 minutes). This figure does, however, indicate the nacelle yaw is dampened to short term variations in wind direction of  $\pm 10^\circ$  in 10 seconds.

Alternator power of the wind turbine in free yaw with untwisted steel spar blades and tip control was recorded for a nominal rotor speed of 31 rpm after the wind turbine had reached free yaw alignment. For this test a 2 speed high slip induction generator was used with no fluid coupling between the gear box and generator. It was set in the high speed mode and the maximum power was set at 90 kW. Drive train slip was measured to be 4% at rated power of 100 kW. The alternator power output for the wind turbine at free yaw alignment is presented in figure 17. The alternator power output of the same wind turbine in active yaw aligned with the wind is also given for comparison. The differences in power for the wind turbine in free yaw at approximately  $-48^\circ$  yaw as compared to active yaw at  $0^\circ$  is readily apparent. The wind turbine in free yaw did reach the same maximum (limit) power output as the wind turbine aligned with the wind, however, at a wind speed 3 m/s higher. Power for the two configurations and at the prevalent wind speeds along with the median free yaw angle are tabulated in table 4. Again, simple power ratio of the wind turbine into the wind to the wind turbine in free yaw as a function yaw angle could be determined that was consistent with the data.

TABLE 4 - WIND TURBINE PERFORMANCE - FREE YAW VS. ACTIVE YAW  
INTO THE WIND - STEEL SPAR BLADES WITH TIP CONTROL  
AT 31 RPM

REF. WIND SPEED (m/s)	AT POWER- FREE YAW (kW)	YAW ANGLE- FREE YAW (DEG.)	ALT. POWER ACTIVE YAW (kW)
5.9	5.7	-49	39.0
6.9	18.4	-50	65.1
7.9	29.9	-50	98.0
8.9	49.0	-47	102.1

### Analysis

An analysis was made of the predicted free yaw behavior of Mod-0 using the MOSTAB-HFW (MODular STABILITY - High Frequency Wind) code. This code is a wind turbine version of a rotorcraft code also called MOSTAB-HFW developed for Air Systems Command (ref 8). In HFW, each rotor blade may be modelled with up to four aeroelastic degrees of freedom and the rotor hub may include teetering. The support for the rotor, however, is assumed to be rigid. Further details of the MOSTAB-HFW code are given in reference 9. The assumed blade distributed properties used to model the Mod-0 having 8-1/2° tilt with twisted aluminum blades described earlier and at 26 rpm are given in Appendix A.

The MOSTAB program predictions of the free yaw alignment angle for the Mod-0 wind turbine, with 8-1/2° nacelle tilt, having teetered fixed pitch twisted aluminum blades, 0° coning and at 26 rpm, were verified with data taken on Mod-0 wind turbine. To determine free yaw alignment, nacelle yaw torques were calculated for various trim yaw angles at wind speeds from 5-9 m/s. Since at free yaw alignment the sum of the yaw torques for the nacelle should be zero, a plot of yaw torques vs. yaw angles should indicate the free yaw alignment at zero yaw torque. With the yaw drive disconnected by a clutch and brake pressure set to 0 PSI, the yaw torques acting would be the torques generated by the rotor and friction torque. The rotor torques were computed by MOSTAB. The friction torque was estimated from experimental data to be 1900 N-M, based on nacelle weight of 1421 kilograms, friction coefficient of .02 and a yaw bearing radius of .69 meters. Figure 18 shows the yaw torques at various yaw angles calculated by MOSTAB for the given wind speed envelope. Also shown is the estimated yaw friction torque. The yaw equilibrium where the sum of the torques are zero and free yaw alignment occurs would be the range of yaw angles where the yaw friction torque intersects MOSTAB's nacelle yaw torque envelope, Figure 18 indicates a range of yaw angles of -55° to -35° where yaw equilibrium may occur depending upon the wind speed. The experimental free yaw alignment of -53.6° falls in that range. Considering the accuracy of the

estimated yaw friction and unsteady meteorological variables in the experimental data, the MOSTAB program predicts reasonably well wind turbine free yaw alignment.

Studies were made with the MOSTAB-HFW code to determine the effects of nacelle tilt, rotor coning and wind shear on wind turbine free yaw alignment. For these cases, a baseline wind turbine configuration was modeled and then one specific characteristic was changed. The resulting values of yaw torque were then compared to the baseline configuration yaw torque values. The baseline model used was the Mod-0 100 kW wind turbine with 8-1/2° nacelle tilt, teetered rotor with 0° coning, and fixed pitch twisted aluminum blades operating at 26 rpm in steady 7 m/s wind speeds. The effect of removing the 8-1/2° of nacelle tilt is shown in figure 19. The MOSTAB calculations show a positive shift of the yaw torque vs. yaw angle curve which indicates the nacelle will align closer to the wind of nacelle tilt is removed. A significant positive shift of the yaw torque vs. yaw angle curve was calculated by MOSTAB for the wind turbine with 7° coning as compared to the baseline wind turbine without coning, as shown in Figure 20. The addition of coning to the baseline model would cause the wind turbine to align closer with the wind. The effect of removing wind shear upon predicted yaw torque vs. yaw angle is small as shown in Figure 21. However, it indicates the wind shear does contribute to the off wind alignment of the wind turbine in free yaw.

## CONCLUSIONS

Free yaw operation of the NASA Mod-0 wind turbine with 8-1/2° nacelle tilt and 0° coning and using both fixed pitch twisted blades and untwisted tip controlled blades resulted in the following conclusions:

1. The wind turbine is stable and damped in free yaw and readily seeks and maintains free yaw alignment at some yaw angle.
2. For the Mod-0 wind turbine configuration with 8-1/2° nacelle tilt, free yaw alignment was between -55° and -45° and independent of wind speeds between 5-9 m/s. The large off wind alignment of the nacelle, is believed to be mostly due to the nacelle tilt.
3. At these yaw angles power output of the wind turbine was reduced 30% to 50% from the power output of the wind turbine aligned with the wind.
4. Free yaw operation with twisted aluminum blades provided slightly more nacelle yaw damping than operation with untwisted steel spar blades with tip control.
5. MOSTAB predictions of free yaw alignment and rotor power correlated reasonably well with experimental data in the case of the Mod-0 wind turbine with twisted aluminum blades at 26 rpm.

6. MOSTAB calculations indicate that both removing tilt and adding coning will cause the Mod-0 wind turbine with teetered, fixed pitch, twisted aluminum blades to align closer to the wind.
7. Wind shear variations have a small affect on free yaw alignment, the less wind shear, the closer alignment to the wind.

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3. Winemiller, J. R.; et al.: Design, Fabrication and Initial Test of a Fixture for Reducing the Natural Frequency of the Mod-0 Wind Turbine Tower. DOE/NASA 1028-79/24, NASA TM-79200, 1979.
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8. Hoffman, John A.: Analysis Methods Incorporated in the MOSTAB-HFA Computer Code. PPI-1013-2, Paragon Pacific, Inc., 1975.
9. Williamson, Dale R.: Design of Articulated Hub Concepts. PPI-1014-10, Vols. I and II, Paragon Pacific, Inc., 1977.

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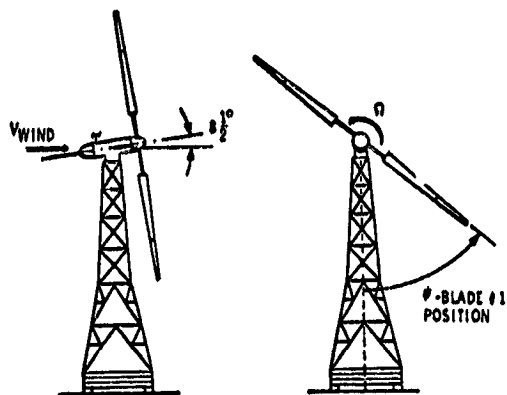


FIGURE 1. NASA MOD-0 WIND TURBINE

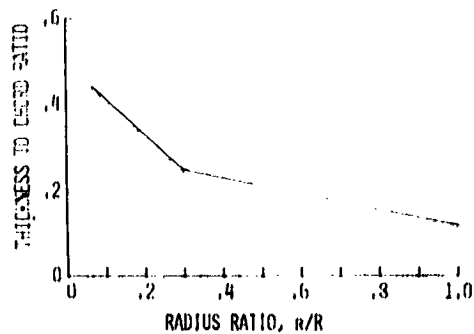


FIG. 4. THICKNESS TO CHORD RATIO  
FOR TWISTED ALUMINUM BLADE.

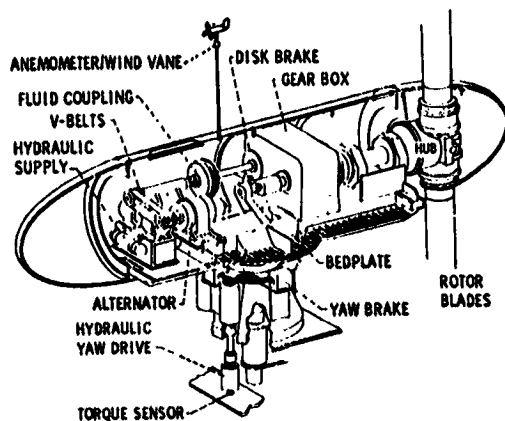


FIGURE 2. NASA MOD-0 WIND TURBINE NACELLE  
INTERIOR WITH TEETERED HUB

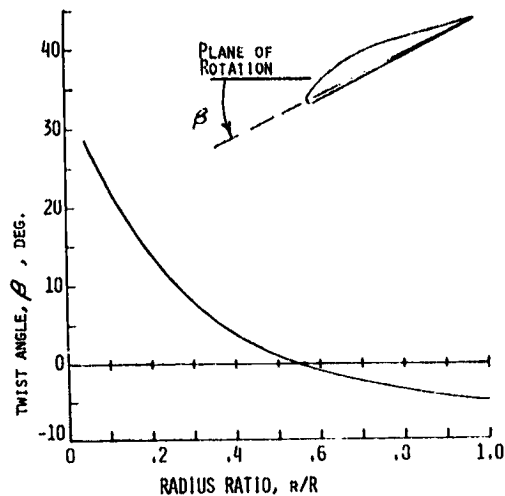


FIG. 5. TWIST DISTRIBUTION FOR  
TWISTED ALUMINUM BLADES.

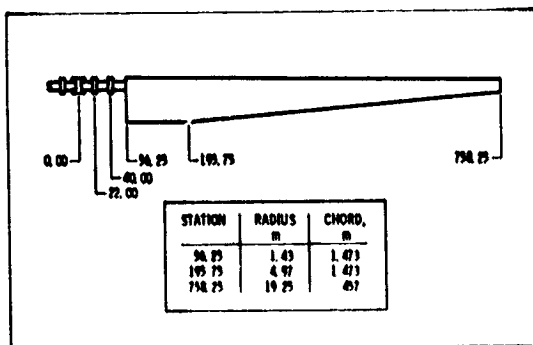


FIG. 3. BLADE PLANFORM TWISTED  
ALUMINUM BLADES

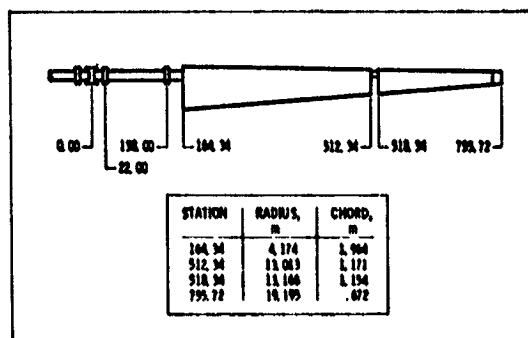


FIG. 6. BLADE PLANFORM - STEEL  
SPAR WITH TIP CONTROL BLADES



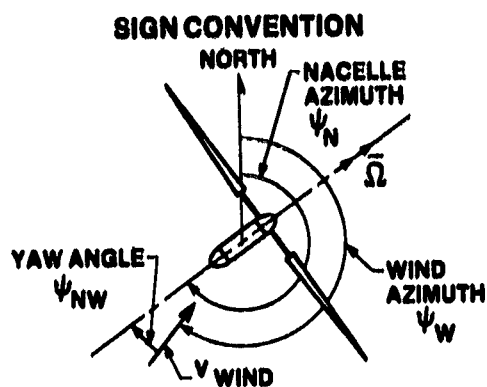


FIGURE 7. MOD-0 NACELLE YAW POSITION SIGN CONVENTIONS

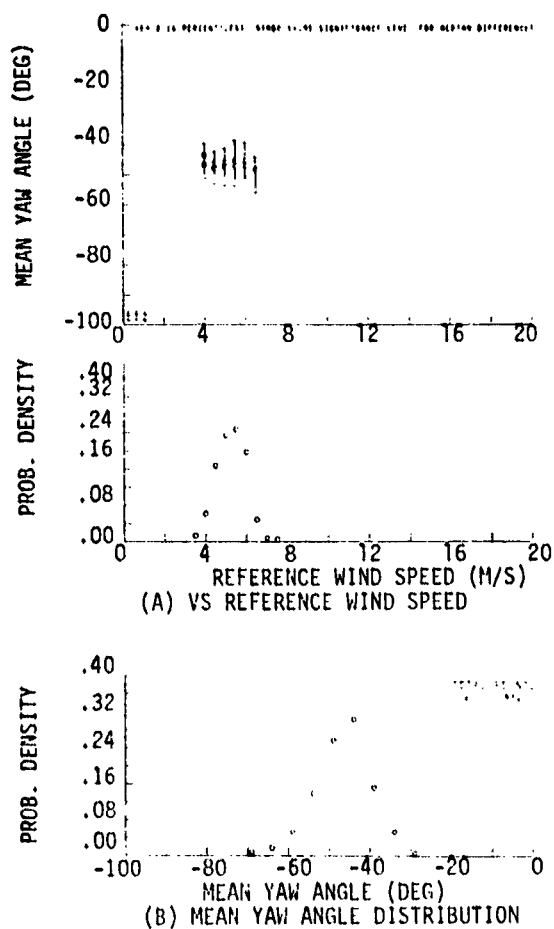


FIG. 8. FREE YAW ALIGNMENT DATA FOR WT WITH TWISTED BLADES AT 20 RPM VS. REFERENCE WIND SPEED (A), AND DISTRIBUTION (B).

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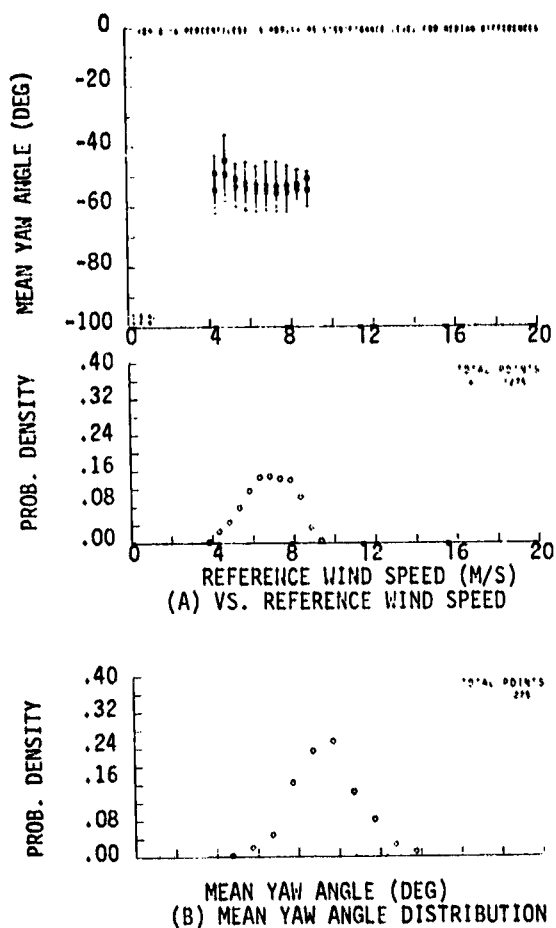


FIG. 9. FREE YAW ALIGNMENT DATA FOR WT WITH TWISTED BLADES AT 26 RPM VS. REFERENCE WIND SPEED (A), AND DISTRIBUTION (B).

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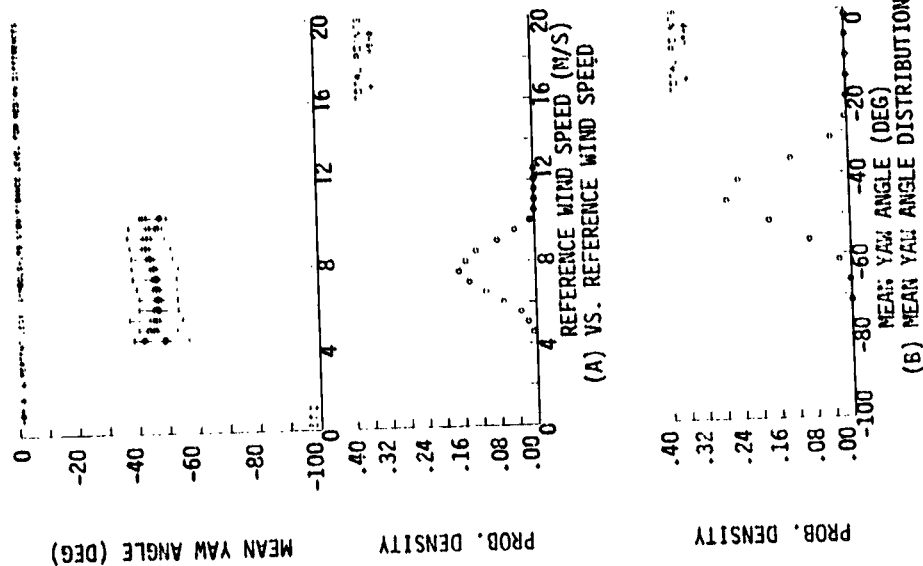


FIG. 10. FREE YAW ALIGNMENT OF WT WITH TWISTED BLADES AT 31 RPM VS. REFERENCE WIND SPEED (A) AND DISTRIBUTION (B).

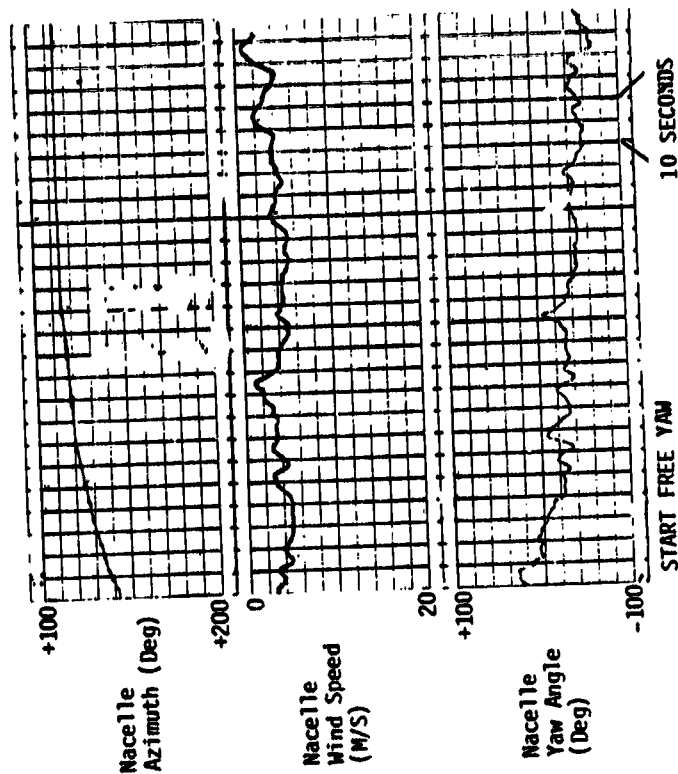


FIG. 11. STRIP CHART RECORDING OF WT WITH TWISTED ALUMINUM BLADES AT 26 RPM PLACED IN FREE YAW AT 00 YAW ANGLE.

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FIG. 12. STRIP CHART RECORDING  
OF WT WITH TWISTED BLADES AT  
26 RPM STABILIZED AT FREE YAW  
ALIGNMENT.

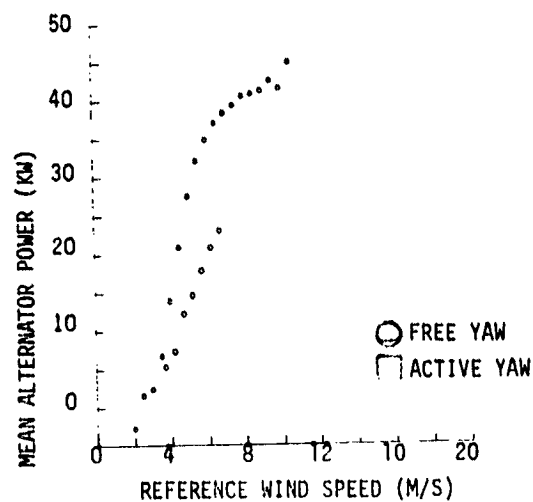


FIG. 13. MEAN ALTERNATOR POWER  
VS. REFERENCE WIND SPEED FOR WT  
WITH TWISTED ALUMINUM BLADES AT  
20 RPM FOR BOTH FREE YAW AND  
ACTIVE YAW INTO THE WIND.

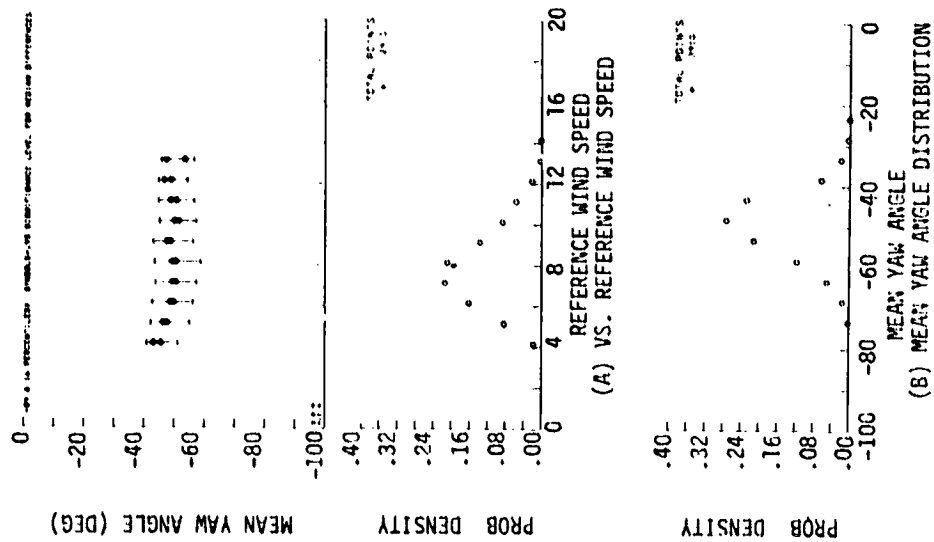


FIG. 14. FREE YAW ALIGNMENT OF WT WITH UNTWISTED BLADES, TIP CONTROL AT 31 RPM VS. REFERENCE WIND SPEED (A) AND DISTRIBUTION (B).

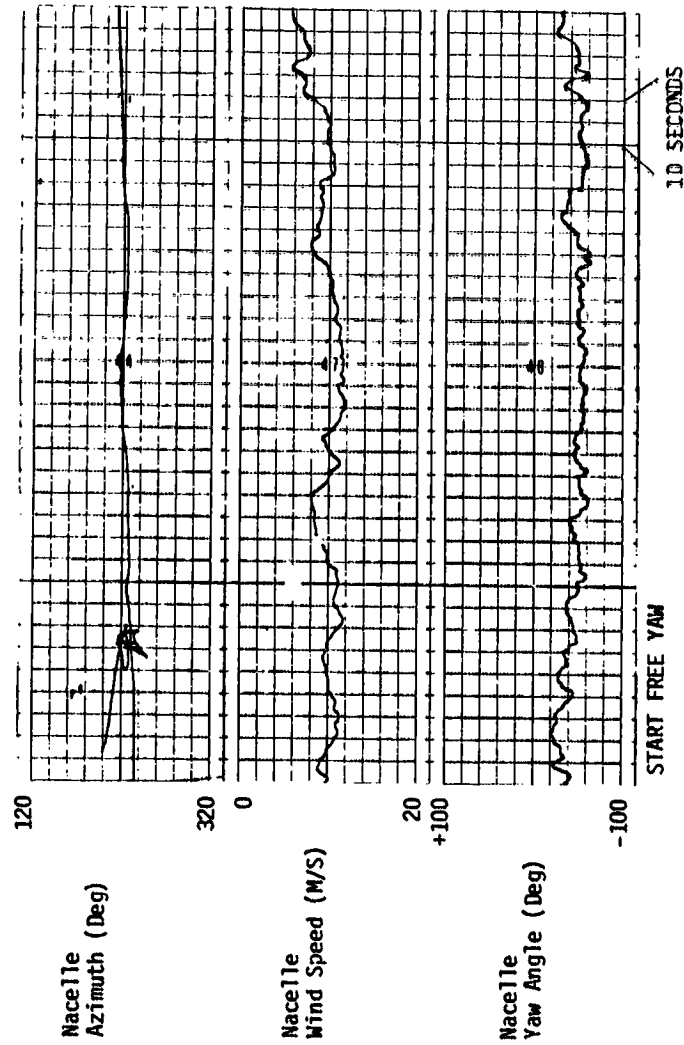


FIG. 15. STRIP CHART RECORDING 3F WT WITH UNTWISTED BLADES, TIP CONTROL AT 31 RPM PLACED IN FREE YAW AT -35° YAW ANGLE.

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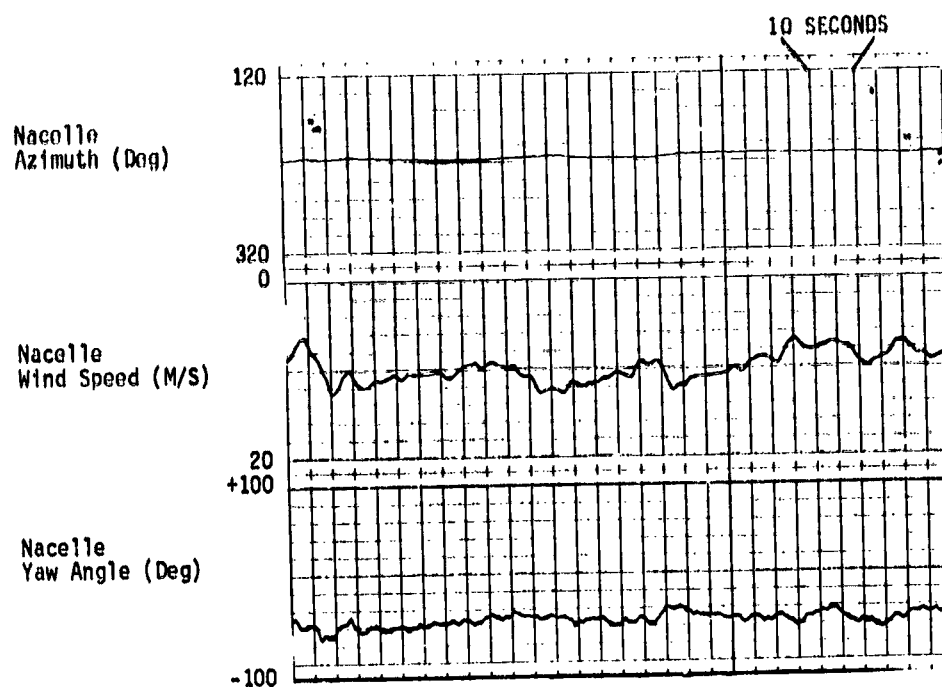


FIG. 16. STRIP CHART RECORDING  
OF WT WITH UNTWISTED BLADES, TIP  
CONTROL AT 31 RPM STABILIZED AT  
FREE YAW ALIGNMENT.

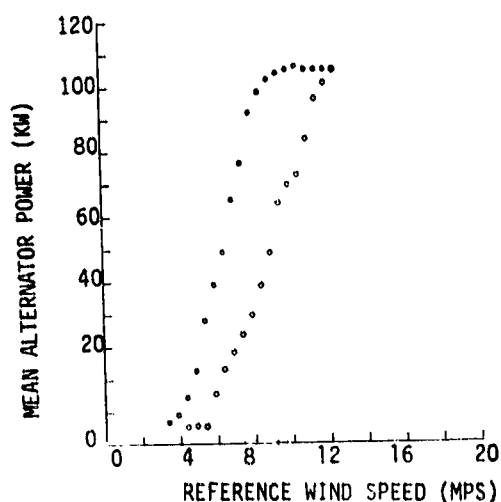


FIG. 17. MEDIAN ALTERNATOR POWER  
VS. REFERENCE WIND SPEED FOR WT  
WITH UNTWISTED BLADES, TIP  
CONTROL AT 31 RPM IN FREE YAW  
AND ACTIVE YAW INTO THE WIND

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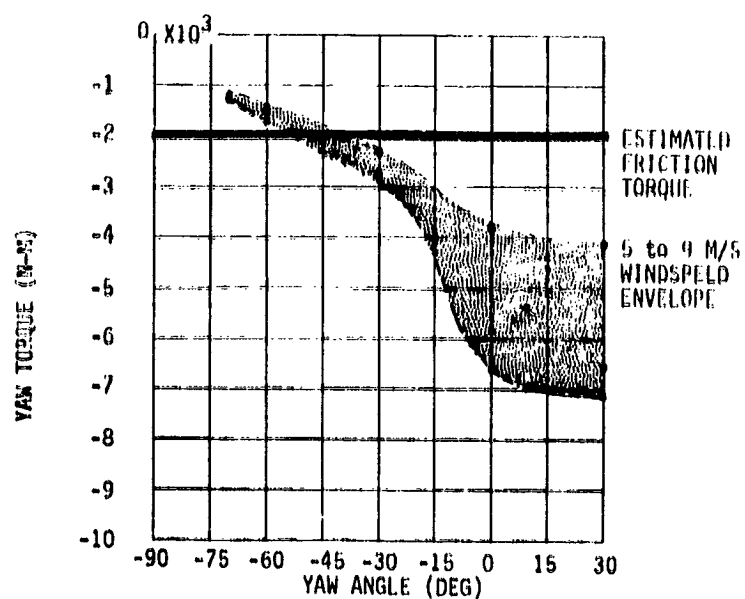


FIG. 18. MOSTAB COMPUTED YAW TORQUE ENVELOPE FOR MOD-0 AT 26 RPM.

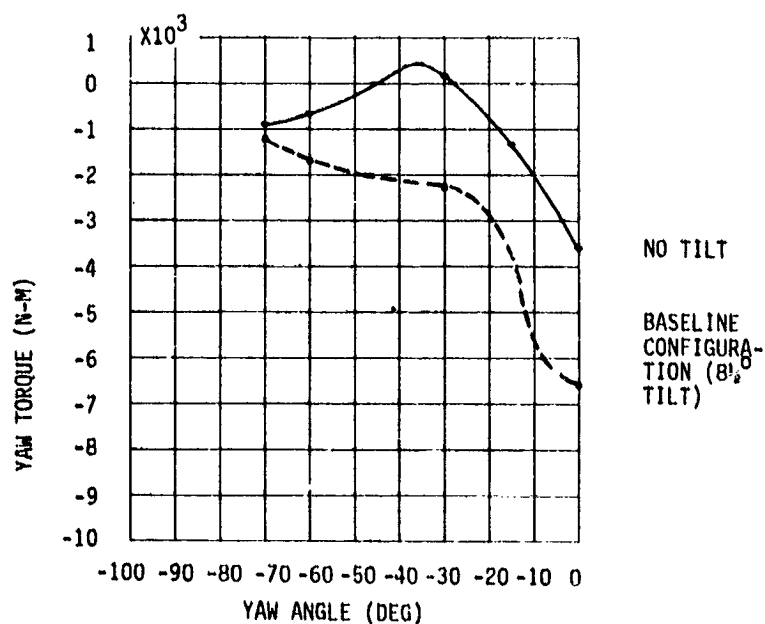


FIG. 19. MOSTAB COMPUTED EFFECTS OF TILT ON YAW TORQUES FOR MOD-0 AT 26 RPM IN 7 M/S WINDS.

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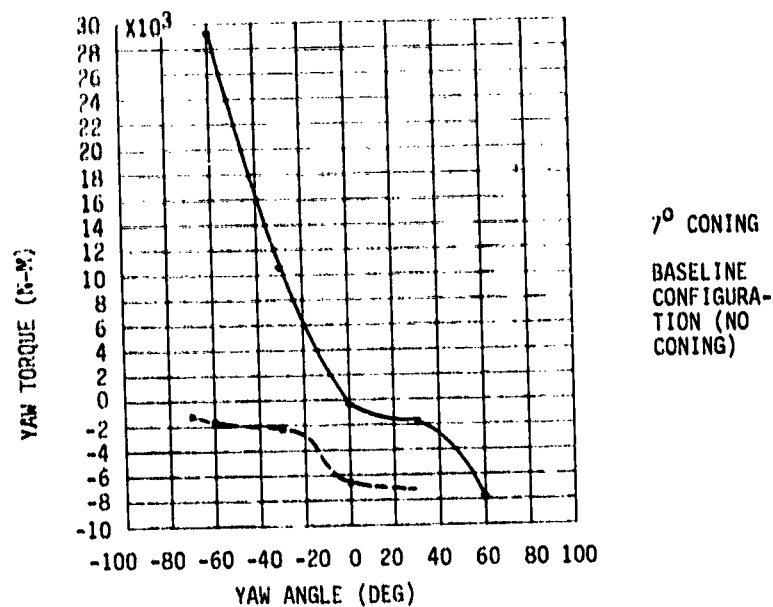


FIG. 20. MOSTAB COMPUTED CONING EFFECT ON YAW TORQUES FOR MOD-0 WT AT 26 RPM IN 7 M/S WIND.

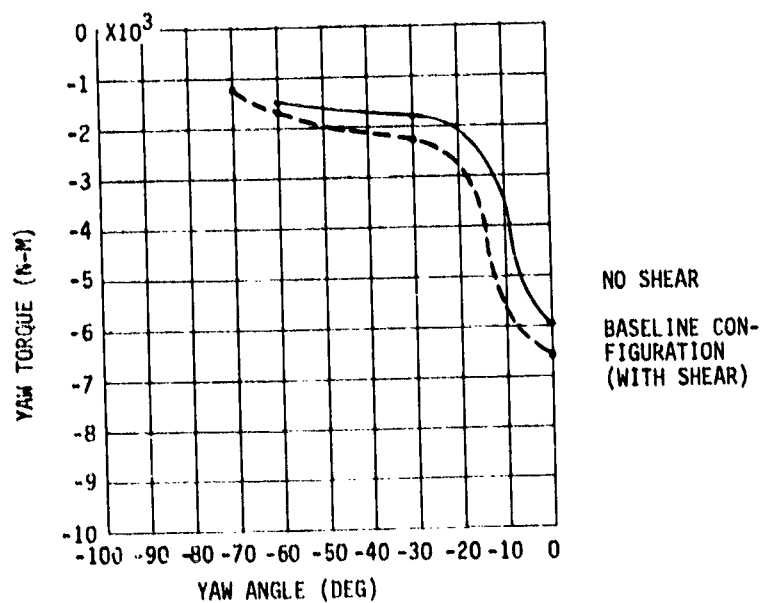


FIG. 21. MOSTAB COMPUTED EFFECT OF SHEAR TORQUES FOR MOD-0 WT AT 26 RPM IN 7 M/S WINDS

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# APPENDIX A

MOSTAB INPUT MODEL OF THE MOD-0 WIND TURBINE  
HAVING 8.5° NACELLE TILT, NO ROTOR CONING AND  
TWISTED FIXED PITCH ALUMINUM BLADES OPERATING  
AT A ROTOR SPEED OF 26 RPM.

MZTP		MOSTAR-HFW		MOD-0 WITH TEETERED HUB				
.0000		.0000		.0000				
.0000		.0000		.0000				
GIMBAL DATA								
.1000+001		.0000		.0000				
.0000		.0000		.0000				
DISTRIBUTED BLADE PROPERTIES FOR AEROELASTIC ROTOR ANALYSIS								
STATION	S	MASS	CHORD	YCG	ZCG	INERTIA TENSORS		
	FT	SLUGS/FT	FT			IYY	IYZ	IZZ
1	.00	.000000	.0000	.000	.000	.000	.000	.000
2	3.33	.000000	.0000	.000	.000	.000	.000	.000
3	4.70	.000000	4.5000	.000	.000	.000	.000	.000
4	6.75	1.82400	4.5000	-.139+000	.000	.103+001	.638+001	.161+001
5	15.63	1.67800	4.5000	-.192+000	.000	.213+000	.220+000	.101+001
6	29.00	1.33900	3.9250	.575+001	.000	.110+000	.109+001	.024+000
7	30.83	1.15200	3.5575	.000	.000	.840+001	.900+002	.702+000
8	37.50	.94620	3.1375	.000	.000	.400+001	.487+002	.424+000
9	46.88	.69590	2.5469	.000	.000	.154+001	.106+002	.239+000
10	50.00	.65290	2.3500	.000	.000	.847+002	.190+002	.176+000
11	56.25	.34840	1.9562	.000	.000	.191+002	.741+003	.625+001
12	59.38	.32570	1.7594	.000	.000	.191+002	.741+003	.625+001
13	62.50	.29040	1.5625	.000	.000	.847+003	.318+003	.477+001
CONCENTRATED MASS PROPERTIES FOR AEROELASTIC ROTOR ANALYSIS								
STATION	S	MASS	YCG	ZCG	IYY	IYZ	IZZ	
	FT	SLUGS						
1	3.33	.894+001	.000	.000	.496+000	.000	.496+000	
2	5.37	.850+001	.000	.000	.133+001	.159+002	.246+001	
3	1.00	.140+002	.000	.330+000	.305+002	.000	.305+002	



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MZTR MOSTAB-HFW MOD-D WITH TEETERED HUB

INITIAL SHAPE FUNCTIONS -				TWIST, RAD			
STATION	S	SW(12)	SW(13)	SW(14)	SW(12)	SW(13)	SW(14)
1	FT.	.000	.000	.000	.000	.000	-.100+001
2	3.33	.000	.000	.000	.000	.000	-.100+001
3	4.00	.000	.000	.556+000	.000	.000	-.100+001
4	6.75	.000	.000	.556+000	.000	.000	-.100+001
5	15.63	.000	.000	.261+000	.000	.000	-.100+001
6	25.00	.000	.000	.119+000	.000	.000	-.100+001
7	30.83	.000	.000	.715+001	.000	.000	-.100+001
8	37.50	.000	.000	.346+001	.000	.000	-.100+001
9	46.88	.000	.000	.000	.000	.000	-.100+001
10	50.00	.000	.000	-.670+002	.000	.000	-.100+001
11	56.25	.000	.000	-.233+001	.000	.000	-.100+001
12	59.38	.000	.000	-.294+001	.000	.000	-.100+001
13	62.50	.000	.000	-.349+001	.000	.000	-.100+001

MODAL DATA-

MODE NO. 1 OMEGA = 11.56470	MODE NO. 2 OMEGA = 15.92200
BETA E = .0000	BETA E = .0000
BETADOT E = .0000	BETADOT E = .0000
INTEGRATION SPECIFICATION = 1.0000	INTEGRATION SPECIFICATION = 1.0000
ZETA = .0000	ZETA = .0000

STATION	S	DEL(12)	DEL(13)	DEL(14)	DEL(12)	DEL(13)	DEL(14)
1	.00	.00000	.00000	.00000	.00000	.00000	.00000
2	3.33	.00240	-.01110	.00000	-.04150	-.00640	.00000
3	4.00	.00450	-.02100	.00000	-.07770	-.01200	.00000
4	6.75	.02180	-.09880	.00000	-.35580	-.04970	.00000
5	15.63	.19140	-.77790	.00000	-2.34370	-.19660	.00000
6	25.00	.59240	-2.48240	.00000	-6.31330	-.50920	.00000
7	30.83	.94570	-4.18330	.00000	-9.66140	-.90970	.00000
8	37.50	1.42020	-6.75450	.00000	-14.16380	-1.65450	.00000
9	46.88	2.18440	-11.74450	.00000	-21.58420	-3.48990	.00000
10	50.00	2.45750	-13.85820	.00000	-24.34090	-4.40380	.00000
11	56.25	3.81710	-18.83740	.00000	-38.24520	-6.80610	.00000
12	59.38	1.29280	-21.84340	.00000	-33.33690	-8.43130	.00000
13	62.50	3.56730	-24.94460	.00000	-36.45700	-10.14320	.00000

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## QUESTIONS AND ANSWERS

R. Corrigan

From: B. Dahlroth

Q: I understand the measurements were done with pitch control. Have you taken any measurements with stall control, i.e. fixed pitch?

A: Yes. *The twisted aluminum blades were fixed pitch and stall limited.*

From: A. C. Hansen

Q: The test data indicate no change in yaw error with wind speed. MOSTAB appears to predict significant dependence of yaw angle upon wind speed (looking at your wind speed envelope). How do you explain this discrepancy and how did you select the wind speed for your predictions?

A: *In looking at the experimental data, I stated the mean yaw angle for free yaw operation appeared fairly independent of wind speed. There could be several reasons for this; one being the limited amount of data with the median wind speed being poorly predicted and biasing the data on both sides. The MOSTAB code is sensitive to wind speed at lower yaw angles, however, as the yaw angle increases above  $-15^\circ$ , this sensitivity is greatly reduced as shown in Figure 18. This can account for the seeming independence of the free yaw alignment angles at  $-45^\circ$  to  $-55^\circ$  to the wind speed. Input wind speed for MOSTAB calculations were based on the wind speed range for experimental data.*

From: R. Pelote

Q: Why was the coned rotor more offset from the wind direction than the untilted and unconed rotor?

A: *The coned rotor was more closely aligned with the wind ( $20^\circ$ ) than the unconed rotor ( $-54^\circ$ ). It was more offset from the wind direction than the untilted case ( $-10^\circ$ ). There are two possibilities that could cause the coned rotor to be more offset than the untilted cases: the effect of 1) tilt associated with the coned wind turbine, or 2) the wind shear model used for the coned wind turbine predictions.*

From: Anonymous

Q: What is the impact on energy capture resulting from operation at approximately  $50^\circ$  of yaw angle?

A: *We noted energy capture losses of 30%-50%, when the turbine yaw angle was this high.*

R. Corrigan (continued)

From: T. Andersen

Q: MOSTAB predicts less yaw misalignment with higher brake friction. Was or will brake friction be added to test this hypothesis?

A: *This is a good test and hopefully we will do it on the MOD-0 wind turbine next quarter.*

From: W. A. M. Jansen

Q: Does the computer program predict a yawing torque if the rotor center to tower axis is zero?

A: *I don't know for certain, but the wind shear and tower interference may cause a yaw torque to be predicted by MOSTAB. Also, nacelle tilt still affect the yaw torque component due to the rotor torque.*

## MULTIPLE AND VARIABLE SPEED ELECTRICAL GENERATOR SYSTEMS FOR LARGE WIND TURBINES

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Westinghouse Electric Corporation  
Pittsburgh, Pennsylvania

### ABSTRACT

A cost-effective method to achieve increased wind turbine generator energy conversion and other operational benefits through variable speed operation is presented. Earlier studies of multiple and variable speed generators in wind turbines have been extended for evaluation in the context of a specific large sized conceptual design. System design and simulation have defined the costs and performance benefits which can be expected from both two speed and variable speed configurations.

### BACKGROUND

A previous paper by the authors(1) reported an examination of the costs and energy capture performance expected for a spectrum of single, two, three, and variable speed generator designs in wind turbine applications. That study concluded that the two speed Westinghouse Pole Amplitude Modulated (PAM) generator could provide a cost effective 13 percent improvement in energy capture and that more expensive variable speed concepts require cost justification beyond their 20 percent energy capture improvement.

The key to the sensitivity of annual energy capture to speed of operation is the variation of the rotor performance coefficient  $C_p$  with the ratio of blade tip speed to wind speed shown in Figure 1. In single, constant speed wind turbine rotor operation, the tip-speed ratio varies inversely with the wind speed, and the efficiency of rotor energy capture of the wind,  $C_p$ , reaches its maximum value at just one point. As shown in Figure 2, continuously variable rotor speed operation between 12.7 and 19 rpm would allow  $C_p$  to be maximized between 7 and 10.5 m/s while two speed operation suffers a 12 percent degradation of 9 m/s.

### TWO SPEED SYSTEM DESIGN

The specifications for comparison of generating systems evaluated are shown in Table 1.

The PAM generator is an asynchronous (induction) alternating current machine with a single stator winding and speeds available in a variety of ratios between one and two. It differs from conventional single speed AC induction generators only in winding design since construction details are identical. PAM is a method of obtaining

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# AERODYNAMIC ROTOR EFFICIENCY CURVE ( $C_p$ )

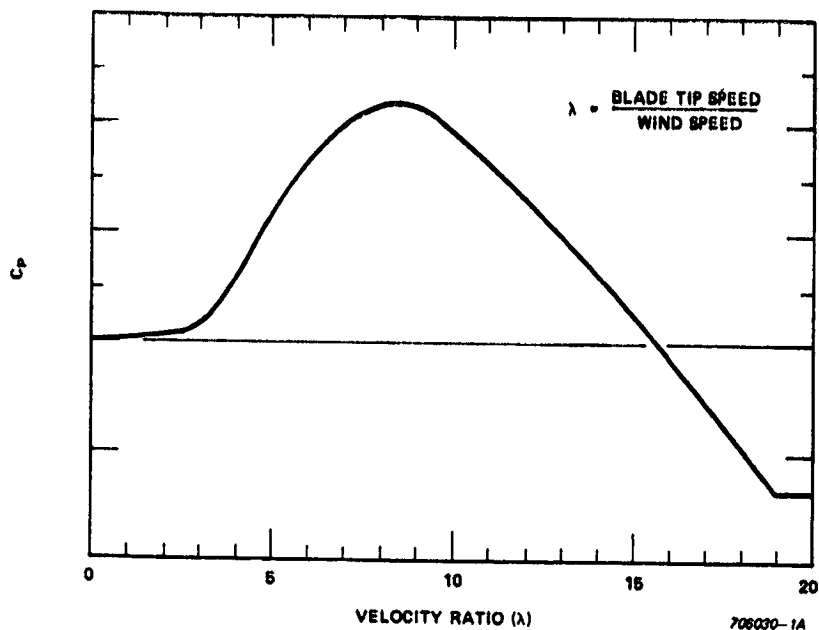


Figure 1

## BLADE EFFICIENCY AS A FUNCTION OF WIND SPEED AND ROTOR SPEED

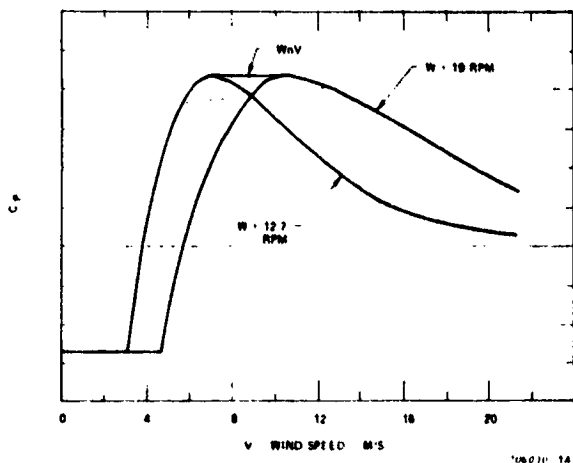


Figure 2

## PAM SCHEMATIC DIAGRAM

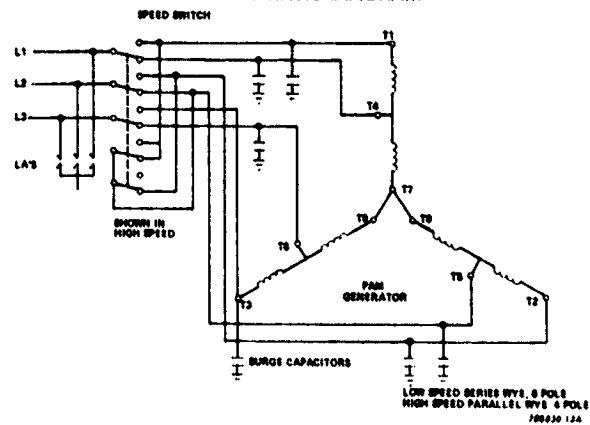


Figure 3

two speeds from a single winding, three phase squirrel cage induction machine. It is accomplished by simply changing the connections to the six main leads of the stator. The internal motor coil connections are not changed, but one half of the coils are reversed in polarity (modulated) and the number of parallels in the motor winding are changed as the main leads are reconnected.

The baseline PAM generator selected for comparison is a 6,000hp, 1800/1200 rpm machine which requires a five pole double throw speed switch to reconfigure the machine windings to achieve four pole and six pole operation. Since the PAM is an induction generator, a bank of capacitors is provided in the design to accommodate the magnetizing current of the machine and provide for power factor correction. Switchgear is located at the interface with the utility to isolate the machine from the network during periods of shutdown and during speed changing operations.

Two sets of winding configurations were evaluated for the baseline PAM. The machine can be configured with the windings for low speed (6 pole) operation series delta and for high speed (4 pole) operation parallel wye. Figure 3 shows the windings for low speed (6 pole) operation series wye connected and for high speed (4 pole) operation parallel wye connected along with the speed switch, surge capacitors, and lightning arresters. As a result of its higher equivalent impedance, use of the series wye configuration for the motoring mode results in minimum inrush current and peak torque and is chosen for the baseline system.

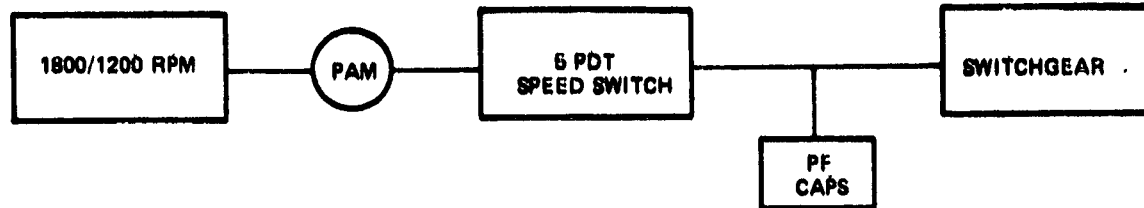
TABLE 1: GENERATING SYSTEM SPECIFICATIONS

- 4400 kW Nameplate Rating
- 25 Percent overload for a period of one hour per day
- 6600 V Terminal Voltage
- Class B Insulation
- Drip proof enclosure
- 3300 ft altitude
- Across the line starting
- Self-starting capability
- 1.37 per unit limitation on drive train torque for frequent occurrences
- Minimum starting torque 77,000 lb-ft

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The cost, size, and weight of the components for the baseline PAM system are shown for a 6600 V system in Figure 4. All costs are based on the 100th unit of a 1,000 unit production run in 1977 dollars.

### BASELINE PAM SYSTEM, DIAGRAM AND COSTS



	GENERATOR	SPEED SWITCH	CAPACITORS..	SWITCHGEAR	TOTAL
*COST, \$	99,463	6,212	5,700	19,654	131,029
SIZE, m	9612 FRAME (6600V)	36 x 34 x 12 x 77	60 x 60 x 60	83 x 40 x 102	
WxLxH, m	61½ x 91½ x 76				
WEIGHT, LBS.	27,505	1,375	1,375	3,000	33,255

\*1977 DOLLARS

Figure 4

706030-4A

### VARIABLE SPEED SYSTEM DESIGN

For this study, consideration was limited to conventional single rotor doubly fed machines with solid state converters. Two types of converters were evaluated: a bidirectional cycloconverter and a unidirectional rectifier-inverter slip power recovery system. The basic configuration for the cycloconverter system is illustrated in Figure 5. The stator of the wound rotor induction machine is tied to the interfacing utility network through a starter which consists of a three-pole contactor, current limiting fuses and the protective relaying required to protect both the wind turbine generating system and the interfacing utility network.

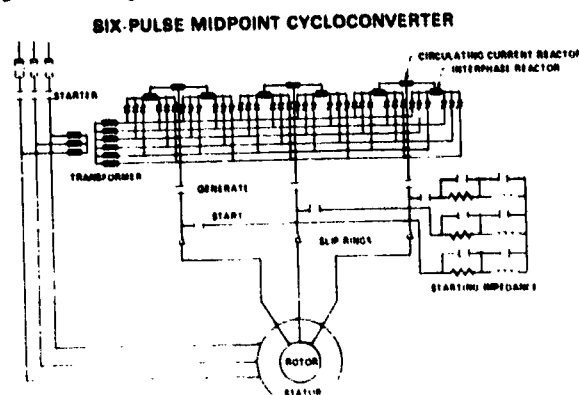


Figure 5

The rotor leads are brought out of the machine through slip rings. Starting impedance and associated contactors are provided in those instances where the wind energy system must be started with the machine in the motoring mode to accelerate the blades to a point where the wind is capable of bringing it within the operating range. Startup as a motor for a doubly fed machine configuration results in relatively low inrush current since the starting impedance can be tailored to the desired characteristics.

In the generating mode the rotor circuit is isolated from the starting impedance and connected, through contactors, to either a cycloconverter or a rectifier inverter depending upon the doubly fed concept utilized. The cycloconverter acts as a frequency changer and provides for power flow both to and from the rotor. When the generator input is less than synchronous speed power flows to the rotor while generator input above synchronous speed results in power flow from the rotor. The rectifier inverter utilized in a slip power recovery system is active only when the generator input is above synchronous speed. The rectifier inverter rectifies the rotor output then inverts it to 60Hz for compatibility with the interfacing network.

Due to the machine winding ratio the rotor voltage is less than the stator voltage. As a result, the voltage level on the 60Hz side of either the cycloconverter or the rectifier inverter is significantly less than the network voltage and a step up transformer provides the interface to the network.

### Cycloconverter Design

Basic cycloconverter designs are available for three, six and twelve pulse systems. In its conceptual designs Westinghouse eliminated all three pulse systems as probably being too rich in undesirable frequencies. The twelve pulse circuits were eliminated since they were considered to be too costly. Among possible circuit configurations, transformer utilization favors a six pulse midpoint cycloconverter configuration as the baseline design. The fundamental specifications for this system are illustrated in Table 2.

TABLE 2: VARIABLE SPEED SYSTEM SPECIFICATIONS

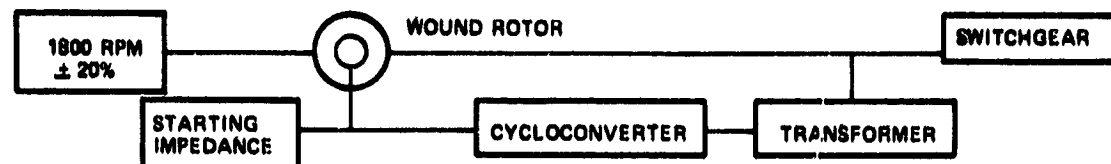
PARAMETER	SYSTEM RATING
System Rated Power	4.4MW
Wound Rotor Machine	4000hp
Synchronous Speed	1800rpm
Speed Range	+ 20%
Primary Voltage	6600V, 3 $\Phi$ , 60Hz
Secondary Voltage -	1650V, 3 $\Phi$
Open Circuit	
Cycloconverter	+12Hz through
Output Frequency	Zero, to -12Hz
Commutation	Line Commutated
Cycloconverter Design	6 Pulse Midpoint



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Data shown on Figure 6 for the cost, size and weight of the principal generating system components reflect costs in 1977 dollars and the scenario of the 100th unit of a 1000 unit production run.

# BASELINE VARIABLE SPEED SYSTEM DIAGRAM AND COSTS



	GENERATOR	CYCLOCONVERTER	STARTING IMPEDANCE	TRANSFORMER	SWITCHGEAR	TOTAL
*COST, \$	126,336	74,038	6,825	8,500	19,664	235,353
SIZE, m	9811 FRAME	48 x 160 x 100	40 x 30 x 90	60 x 60 x 84	83 x 40 x 102	
WxLxH, m	61½ x 83 x 76					
WEIGHT, LBS.	23,660	8,400	2,500	9,400	3,000	46,960

\*1977 DOLLARS

Figure 6

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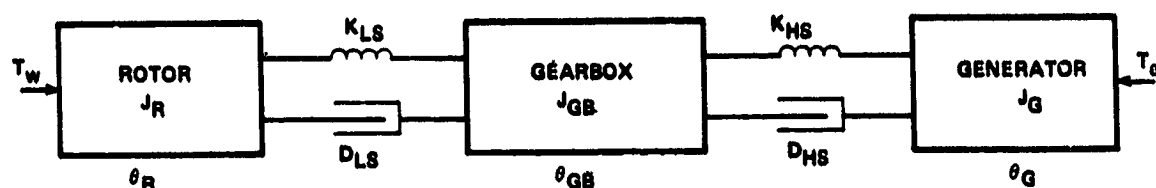
## WIND TURBINE GENERATOR SIMULATION

A complete Wind Turbine Generator model has been implemented on a Westinghouse hybrid computer to evaluate alternative electrical generator systems. Basically, the non-linear items are implemented on the analog consoles while the control and integration features of the model are programmed into the digital portion. The drive train is composed of a blade, a low speed shaft, a gearbox, and a high speed shaft which drives the rotor of the generator. A transmission line network provides system voltage. Generator parameters, namely rotor and stator impedances, are generated in real-time as a function of the slip. A simple cycloconverter simulation provides rotor voltage. Digital computer routines determine wind conditions, speed, torque compensation, and other control commands. The aerodynamic rotor is represented in a simplified fashion by means of a digital computer routine which accepts wind speed input and calculates the wind torque using the  $C_p$  relation of Figure 1. The curve is extrapolated for high velocity ratios to assume negative values to simulate drag under startup and transient conditions.

The 2-p perturbation caused by wind shear effects is modeled on the analog console as a sinusoidal wind torque variation with an amplitude of +25 percent of the wind torque itself. It is added to the output of the wind torque subroutine. Its frequency is determined by the blade speed and changes continuously as the blade speed varies.

The mechanical dynamics of the drive train are simulated as illustrated in Figure 7. The hybrid computer implementation of the model includes drive train efficiency and friction.

### MECHANICAL DYNAMICS MODEL OF THE DRIVE TRAIN



$$J_R \ddot{\theta}_R = T_w + K_{LS} (\theta_{GB} - \theta_R) + D_{LS} (\dot{\theta}_{GB} - \dot{\theta}_R)$$

$$J_G \ddot{\theta}_G = -T_o + K_{HS} (\theta_G - \theta_{GB}) + D_{HS} (\dot{\theta}_G - \dot{\theta}_{GB})$$

$$J_{GB} \ddot{\theta}_{GB} = K_{LS} (\theta_{GB} - \theta_R) + D_{LS} (\dot{\theta}_{GB} - \dot{\theta}_R) + K_{HS} (\theta_G - \theta_{GB}) + D_{HS} (\dot{\theta}_G - \dot{\theta}_{GB})$$

Figure 7

Both 2-speed PAM and variable speed synchronous flux generators are modeled as polyphase induction machines. Generator voltages, current and fluxes are represented in a transformed d-q coordinate system which rotates synchronously with the stator field. The generator parameters, rotor resistance, rotor inductance and stator inductance, are allowed to change with slip. They are generated through a digital computer routine. Separate 4 and 6-pole models are switched in and out by digital control to simulate the two speed PAM. The cycloconverter is controlled so as to vary the rotor voltage in accordance with a control algorithm. Such action produces variations in the generator speed aimed at controlling and stabilizing electrical power output.

### SIMULATION RESULTS

The 2-speed PAM generator configuration was simulated in a number of hypothetical operational situations and found to be very tractable for wind turbine application. Figures 8 and 9 represent a combination of startup, steady state, and speed switching transients. Turbine speed is fully controlled by the electrical generator with no active pitch or other aerodynamic devices. The following sequence of events is illustrated.

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1. Motoring from zero speed in a 6 pole configuration (wind speed = 19 mph).
2. Termination of motoring when the wind torque reaches a 0.1 pu value (Approx. 600 rpm).
3. Aerodynamic acceleration to 1,200 rpm.
4. Steady state generating operation at 1,200 rpm (6 pole).
5. Wind speed increase to 25 mph to trigger pole switching.
6. Generator excitation removal upon pole switch command.
7. Aerodynamic acceleration to 1800 rpm.
8. Return to generator excitation with a 4 pole connection.
9. Steady state generating operation at 1800 rpm.
10. Wind speed decrease to 19 mph to trigger pole switching.
11. 4 pole to 6 pole switch command.
12. Removal of generator excitation for 2 second.
13. Speed increase of approximately 2% (aerodynamic operation) at the end of the 2-second delay.
14. Return to generator excitation with a 6 pole connection.
15. Generator forces deceleration.
16. 14 mph wind gust overcomes generator torque and speed exceeds 1800 rpm.
17. 6 pole to 4 pole switch command.
18. Generator torque sufficient to control speed.
19. Gust subsides - 4 pole to 6 pole switch command.
20. Generator forced deceleration to 1200 rpm.
21. Generator steady state operation at 1200 rpm.

Figures 10, 11, and 12 show typical results obtained from the dynamic simulation of a baseline variable speed wind turbine generator. Figure 10 shows the effect on wind torque produced by a gusty wind and the two per revolution blade shear effects. The figure shows that the rotor excitation can be controlled, through the cycloconverter, to produce a nearly constant power output under the

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**PAM STARTUP AND POLE SWITCHING TRANSIENT  
WITH WIND GUST**

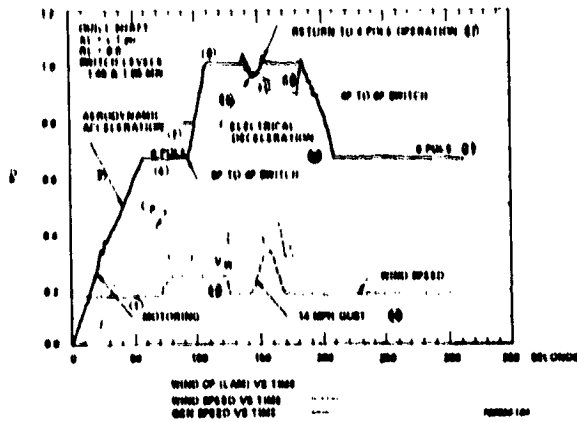


Figure 8

**PAM GENERATOR POWER, TORQUE, AND WIND TORQUE  
STARTUP AND POLE SWITCHING WITH GUST**

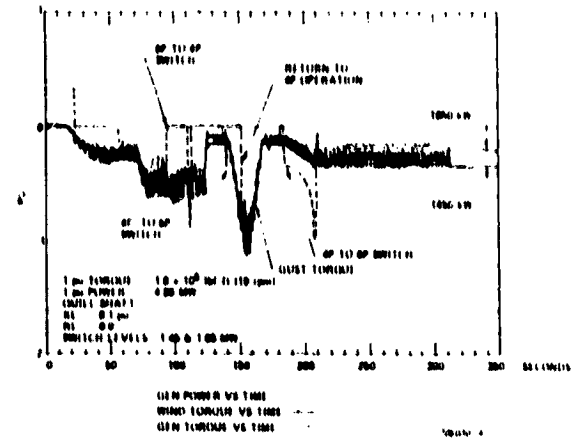


Figure 9

**BASLINE VARIABLE SPEED GENERATOR RESPONSE  
TO WIND TURBINE TORQUE**

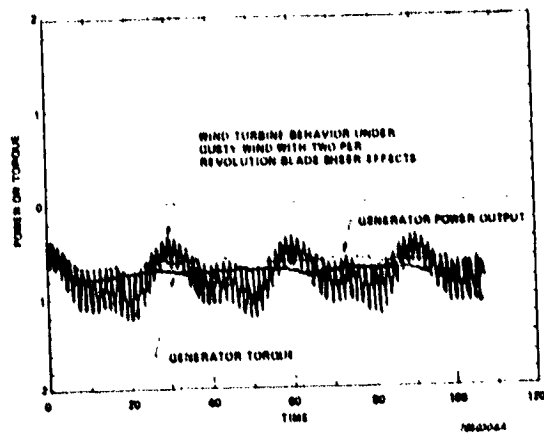


Figure 10

**UNCOMPENSATED VARIABLE SPEED GENERATOR SYSTEM  
RESPONSE TO WIND TURBINE DRIVE TRAIN RESONANCE**

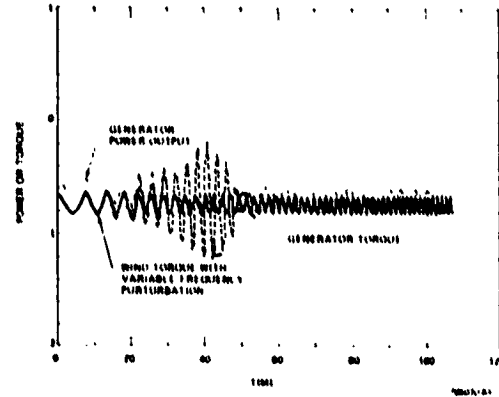


Figure 11

**BASLINE VARIABLE SPEED GENERATOR SYSTEM RESPONSE  
TO WIND TURBINE DRIVE TRAIN RESONANCE**

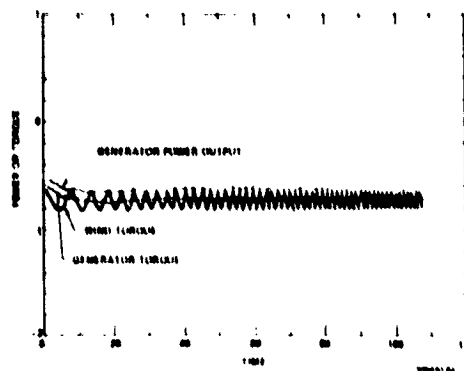


Figure 12

severe wind torque conditions. Figure 11 shows a transient that, by means of varying frequency perturbation on the wind speed, triggers a drive train natural resonance. The resonance is clearly visible and is obtained without making an attempt to compensate for it through the rotor circuit. Figure 12 shows the same transient when variable speed compensation is fully applied. It is seen that the resonance is completely eliminated.

## CONCLUSIONS

Both 2-speed PAM and variable speed baseline generator systems offer attractive benefits to wind turbine performance. Table 3 summarizes the relative advantages and disadvantages of each. Final selection of a generator system, however, must be made in the context of an overall wind turbine design. Table 4 illustrates a generator system selection process. The findings conclude that 2 speed PAM is preferable to single speed provided that further evaluation of switching transients uncovers no adverse impact. The variable speed option is preferred over both single and two-speed if the project schedule allows final development. These conclusions could differ for other wind turbine gearbox and/or blade control configurations.

## REFERENCE

1. T. S. Andersen, H. S. Kirschbaum, Multi-Speed Electrical Generator Application to Wind Turbines, AIAA paper 80-0635-R presented at AIAA/SERI Wind Energy Conference April 10, 1980. J. Energy Vol. 5, May-June 1981, pp. 172-177.

TABLE 3: PAM vs. DOUBLY FED MACHINE WITH CYCLOCONVERTER

PAM GENERATOR	DOUBLY FED MACHINE
<ul style="list-style-type: none"> <li>• ADVANTAGES                             <ul style="list-style-type: none"> <li>• LOWER COST</li> <li>• MINIMUM OF TOWER SLIP RINGS/CABLING</li> <li>• SIMPLER SYSTEM, REQUIRES LESS MAINTENANCE</li> <li>• MORE RELIABLE</li> <li>• STANDARD PRODUCT</li> <li>• SIGNIFICANT EXPERIENCE IN MOTORING MODE</li> <li>• LOWER HARMONICS</li> </ul> </li> <li>• DISADVANTAGES                             <ul style="list-style-type: none"> <li>• TWO SPEEDS</li> <li>• LIMITED DAMPING OF TWO PER REVOLUTION PERTURBATION</li> <li>• POWER FACTOR CONTROL IN DISCREET STEPS</li> <li>• INRUSH CURRENT AT POLE SWITCHING</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• ADVANTAGES                             <ul style="list-style-type: none"> <li>• ELIMINATION OF TWO PER REVOLUTION PERTURBATIONS WITH AND WITHOUT QUILL SHAFT</li> <li>• CONTINUOUS SPEED CONTROL OVER THE OPERATING RANGE</li> <li>• GUST AND TRANSIENT SMOOTHING</li> <li>• MINIMUM OF DRIVE TRAIN COMPONENTS, PERMITS ELIMINATION OF QUILL SHAFT</li> <li>• LOW INRUSH MOTOR STARTING, STARTING IMPEDANCE TAILORED TO DESIRED CHARACTERISTICS</li> <li>• VERSATILE POWER FACTOR CONTROL</li> <li>• MINIMUM TOWER WEIGHT, REDUCED MACHINE SIZE</li> <li>• BEST VARIABLE SPEED CONCEPT</li> <li>• BEST ANNUAL ENERGY CAPTURE</li> <li>• ELIMINATION OF DRIVE TRAIN RESONANCE</li> <li>• 96.5 PERCENT EFFICIENT AT FULL LOAD</li> </ul> </li> <li>• DISADVANTAGES                             <ul style="list-style-type: none"> <li>• GENERATOR OPERATING AT 20 PERCENT ABOVE SYNCHRONOUS SPEED</li> <li>• ADDITIONAL HARDWARE AT TOWER BASE</li> <li>• HIGHER COST</li> <li>• ADDITIONAL TOWER SLIP RINGS/CABLING</li> <li>• HARMONIC DISTORTION (UNDER 5 PERCENT THD)</li> <li>• ADDITIONAL LEAD TIME</li> <li>• GENERATOR SLIP RINGS</li> </ul> </li> </ul>

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TABLE 4: ELECTRICAL GENERATOR SYSTEM TYPE EVALUATION FOR WIND TURBINE APPLICATIONS

TYPE	ADVANTAGES	DISADVANTAGES	SELECTION BASIS	FINDINGS
SINGLE SPEED	<ul style="list-style-type: none"> <li>• Low Cost</li> <li>• Simplicity</li> </ul>	<ul style="list-style-type: none"> <li>• Low Energy Capt.</li> <li>• Low Adaptability</li> </ul>	<ul style="list-style-type: none"> <li>• Does cost benefit overcome performance penalty?</li> </ul>	No
MULTI SPEED	<ul style="list-style-type: none"> <li>• Better Energy Capture</li> <li>• Stepwise Adaptability</li> </ul>	<ul style="list-style-type: none"> <li>• Some Transients and losses during switching</li> </ul>	<ul style="list-style-type: none"> <li>• Are switching transients acceptable?</li> </ul>	Probably, but uncertain
VARIABLE	<ul style="list-style-type: none"> <li>• Best Energy</li> <li>• Minimum Startup and speed change transients or losses</li> <li>• Continuously Adaptable</li> <li>• Provides all necessary Drive Train Damping.</li> </ul>	<ul style="list-style-type: none"> <li>• Real but limited Direct Experience</li> <li>• Relative High Cost</li> <li>• Development Required</li> <li>• More complex structural dynamics</li> </ul>	<ul style="list-style-type: none"> <li>• Do performance advantages outweigh cost?</li> <li>• Is successful development ultimately assured?</li> <li>• Can required development be achieved within commercial wind turbine budget and schedule?</li> <li>• Can remainder of wind turbine accommodate variable speed?</li> </ul>	<p>Yes</p> <p>Yes</p> <p>No Supported Development required</p> <p>Yes</p>

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## QUESTIONS AND ANSWERS

T. S. Anderson

From: R. L. Moment

Q: If added MOD-5 energy capture was outside the scope of your study (verbal answer given to another question), how can you state (in conclusions) that added energy capture justifies additional cost of variable speed generator?

A: *This is the qualitative result of the Boeing studies.*

From: R. Shekar

Q: 1) What is the power rating of the cycloconverter?  
2) Is the power from the cycloconverter fed into the rotor through slip rings?  
3) What is the speed range of the generator?

A: 1) 733 kw (.2 x 4400 kw/1.2).  
2) Yes.  
3) 1440-2160 RPM (1800  $\pm$  20%).

From: W. A. M. Jansen

Q: Did you consider rectifying the current from the synchronous generator and afterwards using power electronics to get proper voltage and frequency?

A: Yes. The combination of starting requirements, controllability and harmonic content weighted against its selection.

From: E. Hinrichsen

Q: What speed variations are allowed at the generator to dampen drive train resonance?

A: Within the  $\pm$  5% control band, indications so far show 1-3%.

From: E. Hinrichsen

Q: Are costs for both systems (PAM and doubly fed) both in 1977 dollars?

A: Yes.

From: C. Rybak

Q: What is the increased energy capture from the variable speed operation?

A: *Specific energy capture was calculated by Boeing.*



T. S. Andersen (continued)

From: P. J. Pekrul

Q: On the two-speed generator, please describe how you "shift gears."  
Does the power drop to zero during rotor speed up and slow down?

A: *The paper contains more information on the shift sequence. A momentary (2-second) power interruption is required.*

From: Anonymous

Q: By what means does the variable speed machine reduce gust induced current surges?

A: *Gust induced current (and torque and power) surges were attenuated by allowing rotor speed to increase, temporarily storing the gust energy much like a flywheel.*

From: Anonymous

Q: What was the variable speed efficiency at lower percentages of rated output?

A: *Efficiency decreased somewhat more sharply than fixed speed induction machines below rated output. Its effect was considered in the overall evaluation.*

From: R. Barton

Q: Why was the speed range limited to  $\pm 20\%$ ?

A: *A 3:1 minimum frequency ratio would allow a total of  $\pm 33\%$  variation, but wind turbine structural considerations and energy capture results indicate little motivation for an operation range beyond  $\pm 20\%$ .*

From: R. Pelote

Q: How does energy capture compare for: single-speed vs. two-speed vs. variable-speed?

A: *Variable-speed - highest, two-speed - medium, single-speed - lowest. Specific energy capture was calculated by Boeing.*

From: R. Pelote

Q: Has Boeing selected the variable speed generator for the MOD-5B?

A: *Yes, at the conclusion of conceptual design.*

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LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Wind Resource Assessments and Siting

Session Chairman - W. R. Barchet (Pacific Northwest Laboratory)

"Putting Wind Resource Atlases to Use"

D. L. Elliott  
(Pacific Northwest Laboratory)

"Approaches to Wind Resource Verification"

W. R. Barchet  
(Pacific Northwest Laboratory)

"Assessing the Representativeness of Wind Data for Wind Turbine Site Evaluation"

D. S. Renné  
(Pacific Northwest Laboratory)  
R. B. Corotis  
(Northwestern University)

"Wind Turbine Siting: A Summary of the State of the Art"

T. R. Hiester  
(Pacific Northwest Laboratory)

## PUTTING WIND RESOURCE ATLASES TO USE

D. L. Elliott  
Pacific Northwest Laboratory  
Richland, WA 99352

## ABSTRACT

An assessment of an area's wind resource and proper site selection are critical to the successful utilization of wind energy. This paper describes how the twelve recently published wind energy resource atlases for the United States and its territories can be used to evaluate various aspects of an area's wind resource. Interpretation of information in the atlas on various geographic scales (regional, state and station) and time scales (annual, seasonal and diurnal) is discussed. In addition to techniques for extracting the magnitude of the wind resource, methods are presented for estimating the seasonal and diurnal variations of the wind resource for an area, the certainty with which the resource has been estimated and the fraction of land area with a given wind resource.

## INTRODUCTION

Wind energy resource atlases have been produced for 12 regions of the United States and its territories. The atlases depict various aspects of the wind resource in graphic, tabular and narrative form. Major users of wind energy resource atlases include: local, state and federal agencies involved in energy planning, private power producers, electric utilities and cooperatives, wind turbine manufacturers and distributors, and energy organizations. The atlases are intended to meet the needs of these and a variety of other users. For ease in use and interpretation, the atlases have been structured in a standard format. Moreover, the atlases were produced using comparable data sets, analysis techniques and presentations to ensure the comparability of the wind resource assessments. For convenience, information on the wind resource is summarized at regional, state, and local scales; however, the assessments are not intended to be site specific. Supplemental information, such as the degree of certainty in the resource estimates and the land area represented by the assessment values, is provided to aid in the interpretation of the resource assessments.

The wind energy resource assessments are based primarily on readily available, summarized, near-surface wind data; upper-air data contri-

buted to the assessments in mountainous areas. The data used in the assessments were obtained from various sources: the National Climatic Center (NCC), the U.S. Forest Service, universities, utilities, and other government and private organizations. The National Climatic Center offered the largest collection of wind data [1]. Screening procedures were applied to identify stations with the most useful data and to eliminate stations that would not significantly contribute information on the resource.

For the purpose of estimating the geographical variation of the wind resource, wind energy flux was chosen over wind speed since the energy flux incorporates in a single number the combined effect of the distribution of wind speeds and the dependence of the energy flux on air density and on the cube of the wind speed. For locations for which the distribution of wind speeds was not available, the energy flux was estimated by assuming the speed distribution followed a Rayleigh distribution [2]. Qualitative indicators of the wind resource aided in estimating the magnitude and extent of the resource in some data-sparse areas. These indicators included the identification of certain combinations of topographical and meteorological features [3], areas containing eolian landforms [4], and areas with flagged trees [5].

The analysis of the wind energy is shown on maps using wind power classes. Each wind power class represents a range of wind energy fluxes (or wind power densities) likely to be encountered. Table 1 gives the wind power classes used in the regional atlases for the 10-m and 50-m reference levels. A 1/7 power law for mean wind speed and 3/7 power law for mean wind energy flux relates the 50-m estimates to the 10-m estimates.

TABLE 1. CLASSES OF WIND POWER DENSITY AT 10 m AND 50 m<sup>(a)</sup>

Wind Power Class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density, watts/m <sup>2</sup>	Speed, <sup>(b)</sup> m/s (mph)	Wind Power Density, watts/m <sup>2</sup>	Speed, <sup>(b)</sup> m/s (mph)
	0	0	0	0
1	100	4.4 (9.8)	200	5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1000	9.4 (21.1)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 5%/5000 ft (3%/1000 m) of elevation.

The analyses of the wind energy resource apply to terrain features that are well exposed to the wind, such as plains, tablelands, hilltops, ridge crests and mountain summits. In wooded or urban areas, the assessment values represent large clearings that are relatively free of obstructions to the wind (e.g., grass, no trees or buildings in immediate vicinity). Local terrain features may interact with the wind-field to cause the wind energy to vary considerably over short distances, especially in coastal, hilly, and mountainous areas. Thus, there may be local areas of higher or lower wind energy than can be shown on the maps. Maps depicting the degree of certainty of the resource estimates are included and should be used in combination with the resource maps.

Because the wind energy estimate generally applies to well-exposed locations, the fraction of the land area represented by the wind power class depends on the physical characteristics of the land-surface form. For example, on a flat open plain close to 100% of the area will have a similar wind power class, while in hilly and mountainous terrain the wind power class will only apply to that small proportion of the land area that is well exposed. Areal distribution maps show the percentage of land area with or exceeding a given wind power class.

The objectives of this paper are to demonstrate the use of the regional atlases to determine six aspects of the wind resource: 1) the magnitude of the wind resource; 2) the certainty of the resource estimate; 3) the fraction of land area that the resource estimate represents; 4) the seasonal variation of the resource; 5) the diurnal variation of the resource; and 6) the prevailing wind direction(s) of the wind resource. The primary intent of this exercise is to provide the user with a better understanding of how to interpret and use the information in the atlases for estimating various aspects of the wind resource in his geographic area of interest.

#### Assessment Area Selected

For demonstrating the use of the resource atlases, an area roughly 100 miles by 100 miles in size has been selected. The area has a wide diversity of land-surface forms, ranging from open plains to high mountains, and a wide range in wind resource estimates and in degrees of certainty of the estimates. Across the nation, numerous types of areas exist, ranging from flat, smooth plains with a fairly uniform wind resource over a large area to mountainous and coastal regions where the resource can vary dramatically over short distances (1 to 5 km). However, this area was chosen as a prime example to demonstrate the interpretation and use of the resource atlases in a variety of scenarios.

#### Estimating the Magnitude of Annual Wind Resource

Figure 1 shows the estimated annual average wind resource at exposed locations in the assessment area. The numbers on the figure refer to the wind power classes given in Table 1. The assessment area is

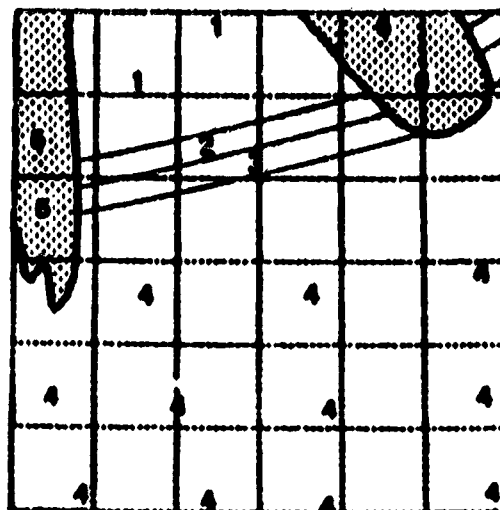


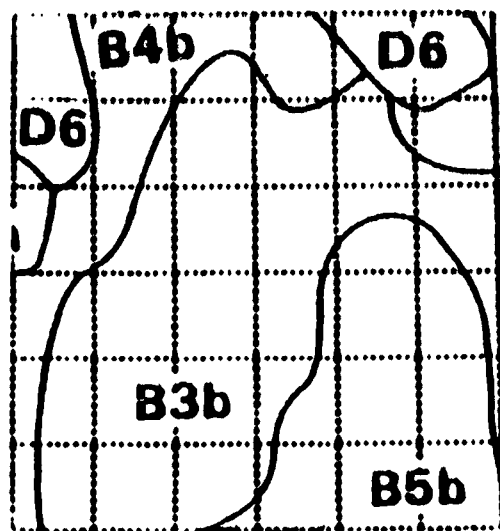
FIGURE 1. ANNUAL AVERAGE WIND RESOURCE. NUMBERS REPRESENT CLASSES OF WIND POWER, WITH "1" THE LOWEST AND "7" THE HIGHEST.

divided into grid cells; each grid cell is  $1/4^\circ$  latitude by  $1/3^\circ$  longitude, which in this case is roughly 17 miles on a side. In the atlases, the grid cells are  $1/4^\circ$  latitude by  $1/3^\circ$  longitude in the conterminous United States,  $1/2^\circ$  latitude by  $1^\circ$  longitude in Alaska, and  $1/8^\circ$  latitude by  $1/8^\circ$  longitude in Hawaii and Puerto Rico. The east-west dimensions of the grid cells vary in size with latitude. The primary purpose of the grids is to aid in locating the area of interest and for ease in switching from one map to another; they are not intended for precise positioning.

A topographic map should be used to determine the relative exposure of the area of interest. Is the area in a lowland or river valley, on a tableland, plateau, or hilltop, or on an open plain with little local relief? A large-scale topographic map, such as a 1:250,000 scale, should be used to determine the relative exposure with respect to major terrain features. In producing the wind resource assessments, sectional aeronautical charts, 1:500,000 scale, were valuable in evaluating general exposure of locations from which data were commonly available. Small-scale topographic maps, such as 15-min maps (1:24,000) can be used to determine local exposure with respect to small-scale features (e.g., bluffs, small hills, etc.).

The analysis shows that class 4 wind power is estimated for exposed areas over most of the region in Figure 1, with areas of class 1, 5, and 6 wind power in the northern portion. What exposed features do the map values represent? Figure 2 is a land-surface form map, which shows the general character of the terrain [6]. Table 2 gives the exposed feature represented by the map value for a variety of land-surface forms. As shown in Figure 2, the region of interest is primarily composed of plains with hills, high hills, and low mountains, and two areas of high mountains. The class 5 and 6 areas on the wind resource map in Figure 1 are shaded, which means that the estimates are for exposed ridge crests and mountain summits. Referring back to the

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B3b - Plains with Hills  
B4b - Plains with High Hills  
B5b - Plains with Low Mountains  
D6 - High Mountains

FIGURE 2. LAND-SURFACE FORM

TABLE 2. LAND-SURFACE FORM TERRAIN FEATURES  
REPRESENTATIVE OF EXPOSED LOCATIONS

Land-Surface Form	Exposed Feature (Map Value)	Percentage Area <sup>(a)</sup>
Plains: A1; B1,2	Plains	93
Plains With Hills: A, B3a,b	Open Plains	79
Plains With Mountains: B4-6a,b	Plains (not shaded) <sup>(b)</sup>	67
	Ridge Crests and Mountain Summits (shaded)	10
Tablelands: B3-6c,d	Tablelands, uplands	80
Open Hills: C2-4	Hilltops and Uplands	27
Open Mountains: C5-6	Broad Valleys (not shaded)	80
	Ridge Crests and Mountain Summits (shaded)	12
Hills: D3-4	Hilltops and Uplands	9
Mountains: D5-6	Ridge Crests and Mountain Summits (shaded)	3

<sup>(a)</sup>Percentage represents an average over the land-surface forms found in the region.

<sup>(b)</sup>Shaded areas on the wind maps, emphasize that map values are estimates for ridge crests and mountain summit locations.

land-surface form map, we find that those class 5 and 6 areas are generally high mountains with vertical relief of 900 to 1500 m (3000 to 5000 ft). Valleys and canyons in these areas will generally have considerably lower wind resource, e.g., only class 1 or 2 power.

Over the remainder of the wind resource map, the class 1 through 4 estimates mostly represent exposed plains (see Figure 2 and Table 2). Hills and low mountains are scattered throughout portions of the plains, as indicated by the land-surface form map. However, these smaller-scale terrain features are not shown on the wind resource map. Hilltops and ridge crests within the plains area may have at least one or two classes higher wind power than that of the plains. Conversely, locations that are in small depressions or are shielded by local terrain features (e.g., hills, mesas, low mountains) will have lower wind power than that indicated by the map values.

As an example of how local terrain effects the wind resource, consider stations A and B in Figure 3. These are two stations with long-term (5 yr or more) digitized hourly or 3-hourly wind data. Both are located in plains areas that are estimated to have the same wind resource (class 4). Table 3 lists the 10-m annual average wind speed and power computed from the hourly data for the two stations. Station A has considerably higher wind power than Station B. Station A has about the same wind resource (class 4-5) as that indicated by the wind resource map, whereas Station B has a lower wind resource (class 2-3). Why is one station represented by the wind power class given in Figure 1 and not the other station, even though both stations are supposedly in the plains? Consulting the station descriptions given in the wind energy resource atlas and identifying the station locations on topographic maps, one finds that Station A is better exposed to the prevailing strong winds than Station B. Station A is located on a plateau that is well-exposed to the wind. Station B, however, is located in a shallow basin with hills and ridges 10 to 15 km away in nearly all directions. Westerly winds (which are the prevailing strong winds in that region) at Station B appear to be diminished by hills and ridges which are about 300 to 400 m (1000 to 1200 ft) higher than the station. Thus, Station A appears representative of the wind resource at well-exposed sites in the open plains, whereas Station B is not so well exposed. Nevertheless, the wind resource information for Station B was still used in qualitatively estimating the wind resource at exposed areas near Station B, assuming that a well-exposed site should have about 1 to 2 classes greater wind power than Station B. Of course, the certainty of the resource at exposed areas is greater near Station A than near Station B. The following section discusses how to use and interpret the certainty rating maps.

#### Certainty Rating of the Wind Resource

The degree of certainty with which the wind power class at exposed sites can be specified depends on three factors: 1) the abundance and quality of wind data; 2) the complexity of the terrain; and 3) the geographical variability of the resource.



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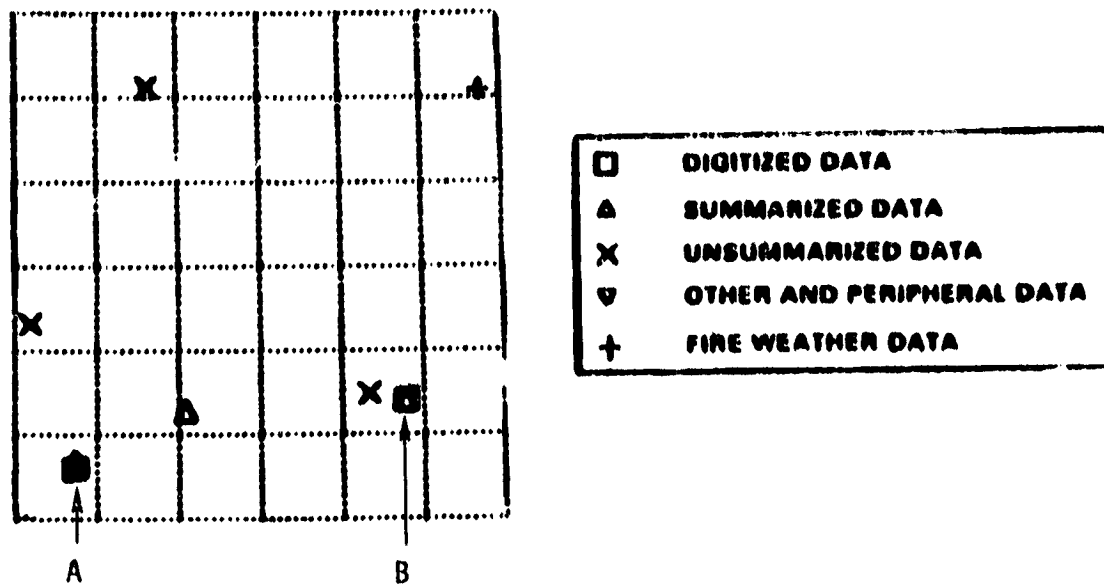


FIGURE 3. STATIONS USED IN ASSESSMENT AREA

TABLE 3. ANNUAL AVERAGE WIND SPEED AND POWER AT TWO STATIONS IN AREA

Station	10 m Speed (m/s)	10 m Power (W/m <sup>2</sup> )	Power <sup>(a)</sup> Class
A	6.1	242	4-5
B	5.3	167	2-3

(a) Power class determined from 10 m power  $\pm$  25 W/m<sup>2</sup>

In the atlases, a certainty rating from 1 (low) to 4 (high) of wind energy resource estimate is given for each grid cell. Certainty ratings are shown in Figure 4 for the area of interest. The assignment of a certainty rating, as defined in Table 4, requires the subjective evaluation of the factors involved. In Figure 4, the certainty ratings of the resource estimates range from 1 (low) to 4 (high). A certainty of 1 has been assigned to that region where the wind resource estimates change from class 4 to class 1 and no data exists at exposed sites. The only cells with a high certainty of the wind resource estimate are near Station A, where data from this well-exposed site can be confidently applied to estimate the resource in nearby areas because of the low complexity of the terrain and low variability of the resource. Other cells in which stations exist have been assigned a certainty of 2 or 3. Some of the stations may have limited data (e.g., unsummarized, daytime only, short period of record, etc.) which can only be used as an indicator of the wind resource. Other stations, such as Station B, may not be representative of a well-exposed site, but serve as a qualitative indicator for estimating the resource at exposed areas. The

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2	3	2	2	2	2
2	1	1	1	1	1
2	1	1	1	1	2
2	2	2	2	2	2
3	3	3	3	3	3
4	4	3	2	2	2

FIGURE 4. CERTAINTY RATING OF RESOURCE. NUMBERS REPRESENT DEGREE OF CERTAINTY OF THE WIND RESOURCE: 1 - LOW; 2 - LOW-INTERMEDIATE; 3 - HIGH-INTERMEDIATE; 4 - HIGH.

TABLE 4. CERTAINTY RATING LEGEND

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exists: <ul style="list-style-type: none"> <li>1) No data exist in the vicinity of the cell.</li> <li>2) The terrain is highly complex.</li> <li>3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.</li> </ul>
2	A low intermediate degree of certainty. One of the following conditions exists: <ul style="list-style-type: none"> <li>1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data.</li> <li>2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.</li> </ul>
3	A high intermediate degree of certainty. One of the following conditions exists: <ul style="list-style-type: none"> <li>1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data.</li> <li>2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.</li> </ul>
4	The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.

ridge crest and mountain summit resource estimates (the shaded areas in Figure 1) were assigned a certainty rating of 2, because upper air data were used to approximate the resource in these areas.

Each state chapter in the resource atlases contains a description of the certainty rating maps and usually includes interpretations on the certainty rating assigned. Because the certainty rating required the subjective evaluation of the interaction of the factors involved, there may be some variation among the different regional atlases in the evaluation of the various factors and in the certainty ratings assigned. For these reasons, certainty ratings may not always match along state or regional borders.

The wind resource maps should always be used in combination with the certainty rating maps. In areas of high certainty, one should not imply that the resource is known and that no further information or data is required. The assessments are not site specific. Moreover, assumptions on the representativeness and exposure of a station's data may, in some cases, bias the estimates. Influences of local obstructions, such as trees, buildings, and terrain, are usually unknown. In some cases, apparently well-exposed stations with long-term data (e.g., 10 to 30 yr) have been found to show questionable trends, such as increasing or decreasing mean wind speeds over a long period of time. This is not to say that measurements at the prospective site are always needed to improve the certainty of the resource. What's important is to understand the particular set(s) of data and information that were used in estimating the resource in the area of interest and to understand the meteorology of the area. Over regions of extreme variability in the resource, an almost infinite number of measurement stations may be needed to fully characterize the resource over the area; whereas over flat regions of uniform resource, few, if any, additional measurement stations may be needed, provided the data used are actually representative in the first place.

#### Estimating the Areal Distribution of the Resource

Because the wind power class values shown on the maps apply only to areas well exposed to the wind, the map area does not indicate the true land area experiencing this power. The fraction of the land area represented by the wind power class depends on the physical characteristics of the land-surface form. For example, on a flat open plain close to 100% of the area will have a similar wind power class, while in hilly and mountainous areas the wind power class will only apply to a small proportion of the area that is well exposed. For each land-surface form, the fraction of land area that would be representative of exposed locations has been estimated (see Table 2 for averages in various land-surface forms). Furthermore, to be able to establish a wind power class for the remaining area, it was also necessary to determine a factor by which the wind power was reduced in the less exposed areas or increased in better exposed areas (e.g., isolated hills and ridges that rise above a plain may experience a higher wind power class than the map indicates). To adjust the wind energy flux from the map value to the various exposure categories, the energy flux

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was scaled to be 1) greater than, 2) equal to, 3) slightly less than, and 4) much less than the map value. Greater detail on these scaling and partitioning procedures are given in the wind energy resource atlases.

In the regional atlases, a representation of the areal distribution is given in a map that indicates the percentage land area in a cell over which the wind power class equals or exceeds a threshold value. Four maps are shown in the chapters on the state wind resources for threshold values of classes 2, 3, 4, and 5. These maps refer only to the annual average resource.

For the area of interest, Figure 5 shows the estimated percent land area in each cell with or exceeding power class 4. Over much of the B3b area (plains with hills - see Figure 2), 80% of the land area is estimated to have wind power class 4 or higher. However, only 2% of the land area is estimated to have class 4 or higher power in the mountainous regions indicating class 5 and 6 wind resource in Figure 1. If a cell contained two or more land-surface forms, then the land-surface form which occupied most of the cell to which the map value pertained was generally chosen. The areal distribution derived from the wind power and land-surface form maps must be considered only an approximation. The quantity and quality of wind data and topographic information required to make a highly accurate appraisal of the areal distribution of the wind resource are far beyond the scope of these assessments.

## CLASS 4

2	0	0	0	2	2
2	0	0	5	5	65
10	68	80	80	80	80
68	80	80	80	65	65
68	80	80	80	65	65
68	80	80	80	65	65

FIGURE 5. AREAL DISTRIBUTION OF RESOURCE. NUMBERS REPRESENT PERCENT LAND AREA WITH OR EXCEEDING WIND POWER CLASS 4.

### Estimating the Seasonal Variation of the Resource

In each state chapter of the regional atlases, maps of the average wind power class are presented for each season: winter (December, January, February); spring (March, April, May); summer (June, July, August); and autumn (September, October, November). For the area of interest, the four seasonal maps are shown in Figure 6. On these maps, the northern basin shows little seasonal variation (class 1 and 2 throughout the year), whereas the wind resource over most of the plains varies from class 6 in winter to only class 2 in summer. This exemplifies the fact that seasonal variation can vary over short distances. Local variations in the wind resource (of a scale too small to be shown on these maps) are often greater in winter than other seasons, as a result of more stable atmospheric conditions. Moreover, the 1/7 power law (3/7 for energy flux) may not be as applicable to vertically adjusting the seasonal average wind resource estimates as it is to the annual average resource. However, the 1/7 power law was used nationwide for the adjusting seasonal average resource estimates because of the lack of sufficient information on the geographical and seasonal variation of the wind profile with height at exposed sites. Thus, the certainty ratings of the seasonal average resource estimates (which have not been determined in these regional assessments) are expected to be lower, in general, than the certainty ratings of the annual average wind resource. Moreover, the distribution of the certainty ratings may change seasonally as the distribution of the wind resource estimates change, e.g., as the spatial variability of the resource over an area increases, the certainty of the resource in that area usually decreases.

To evaluate seasonal trends more directly for a particular area or cell, one could plot the wind power class values for each season and connect the points. For adjusting the seasonal estimates to better or less exposed areas than that typically represented by the map value, one should keep in mind that the variations in resource with terrain height and local terrain influences are usually greater during the colder (more stable) months. As an example here, the difference in the wind resource between Station A (well exposed) and Station B (in a shallow basin) is greater in the winter than in the spring. Station A's winter and spring average wind energy fluxes are  $366 \text{ W/m}^2$  (class 6) and  $244 \text{ W/m}^2$  (class 4-5), respectively, while Station B's are  $235 \text{ W/m}^2$  (class 4-5) and  $198 \text{ W/m}^2$  (class 3-4), respectively. Thus, the ratio of the winter to spring wind energy flux is 1.50 at Station A and 1.19 at Station B, which indicates that the seasonal trends of the wind resource vary locally as terrain and exposure conditions vary. This effect is highly pronounced between ridge crests and valley bottoms, which may have opposite seasonal trends in wind resource.

In the regional atlases, graphs of monthly average wind power and speed for selected stations with digitized hourly or 3-hourly data are presented. Caution should be used in the interpretation and application of these graphs. Stations with less than 5 yr of observations may not show reliable monthly or seasonal trends. Also, stations in complex terrain may not represent the monthly/seasonal trends in nearby areas.

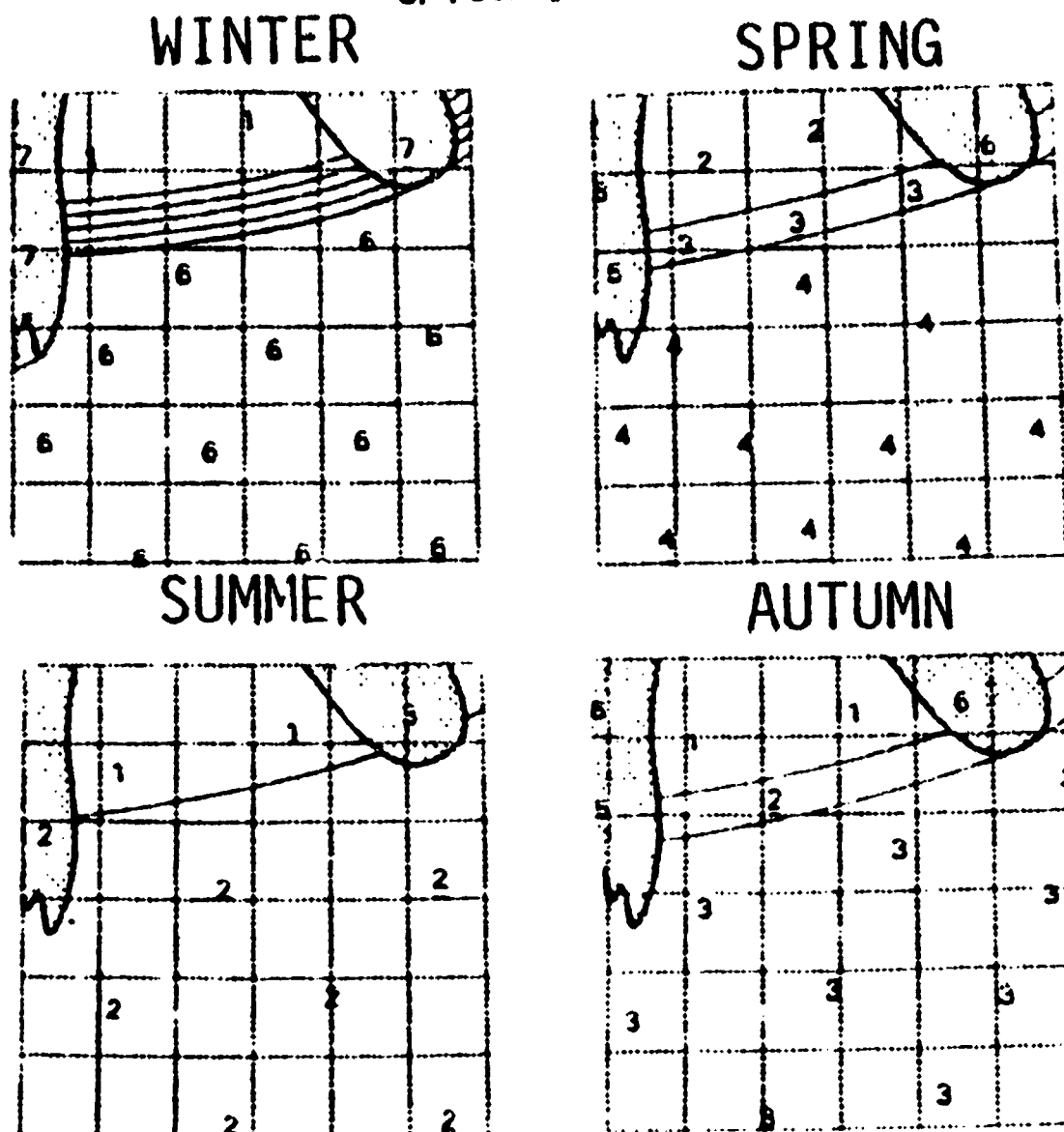


FIGURE 6. SEASONAL AVERAGE WIND RESOURCE

#### Estimating the Diurnal Variation of the Resource

The diurnal variation of the wind resource at a site typically changes with season and height above ground. Influences of terrain and water bodies cause the diurnal winds to vary locally. Examples of this are drainage winds and sea breezes. Although no maps of the diurnal wind resource are presented in the regional atlases, graphs of the diurnal variation of wind speeds by season are shown for selected stations in each state chapter. Again, caution should be used in applying these diurnal characteristics to nearby areas, especially in hilly, mountainous, and coastal areas. Maximum wind speeds on ridge crests and mountain summits are frequently at night, whereas valley, basins, and open plains typically have afternoon maximum winds.

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Figure 7 shows the diurnal variation of wind speeds at Stations A and B. No attempt was made to adjust these data to 10 m or 50 m because of uncertainties in the height variations of the mean wind throughout the day in each season. Typically, the wind shear is considerably greater during night and early morning hours than during the afternoon and early evening hours. At Station A, the diurnal variation is largest in the summer and the smallest in the winter. Since Station A is in a well-exposed location on an open plain, nearby areas with similar exposure can be expected to have similar diurnal variations. At Station B, which is in a shallow basin surrounded by hills and ridges, afternoon mean wind speeds in the spring exceed those in the winter. The diurnal variation of wind speed at exposed hilltops and ridge crests near Station B may be considerably different than that at Station B. These examples demonstrate the importance of knowing a station's exposure (with respect to local terrain, water bodies, etc.) and the meteorology of the area before attempting to apply the diurnal characteristics to nearby areas.

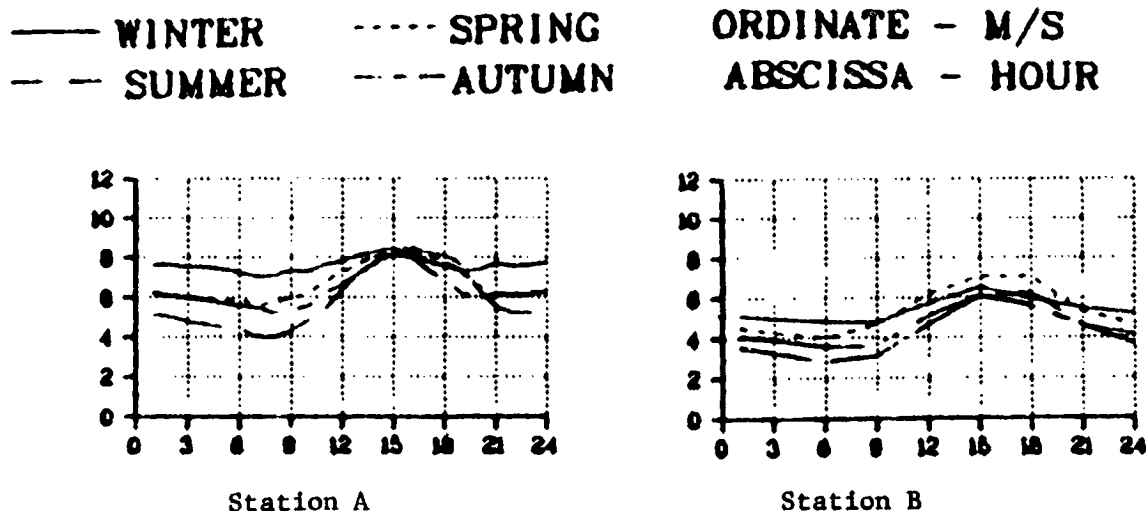


FIGURE 7. DIURNAL VARIATION OF WIND SPEEDS BY SEASON AT TWO STATIONS IN AREA

Estimating the Prevailing Wind Directions of the Resource

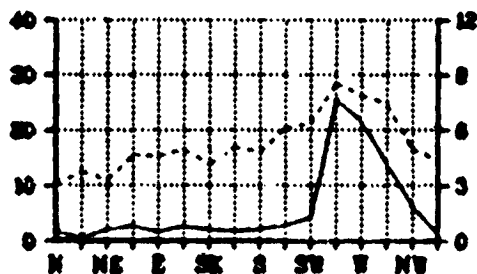
In siting wind turbines, a very important consideration is the prevailing direction(s) of the strong power-producing winds. The prevailing or most frequent wind direction may not be the direction with the highest percentage of wind energy. Thus, standard wind roses which only show the frequency of wind direction are not very useful. In the regional atlases, graphs for selected stations show the percentage of time that the observed wind direction was from each of 16-point compass sectors and the average speed of all observations in each sector. The coincidence of peaks in the two curves indicates that the highest wind speeds occur from the prevailing directions. Again, caution should be

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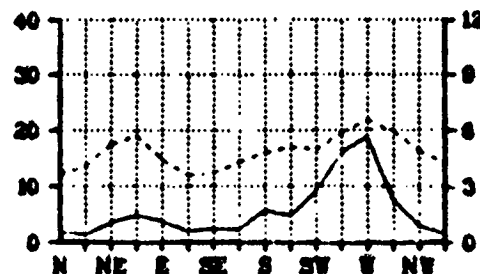
used in applying these data to other sites, because nearby terrain and obstructions strongly influence the wind directions. Some of the directional data presented may not be reliable or representative because of the anemometer location.

Figure 8 shows the directional frequency and average speed for Stations A and B. At Station A, the most frequent prevailing strong winds are from the west-southwest and west. Because Station A is a well-exposed site on an open plain with no apparent terrain obstructions nearby, the directional data should be applicable to nearby areas with similar exposure. At Station B, the prevailing strong winds are also from the west-southwest; although moderately strong winds from the east-northeast occur, they are much less frequent than those from the west-southwest. Because of Station B's location, there may be some local terrain influences on the wind direction. However, these are not readily apparent from the graphs and topographic maps of Station B.

— PERCENT FREQUENCY      LEFT ORDINATE - PERCENT  
..... WIND SPEED      RIGHT ORDINATE - M/S  
ABSCISSA - WIND DIRECTION



Station A



Station B

FIGURE 8. DIRECTIONAL FREQUENCY AND AVERAGE SPEED  
AT TWO STATIONS IN AREA

Considering the directional frequency and speed data from both Station's A and B and other stations in the region, it appears that the areas with the highest wind energy potential are those well exposed to westerly winds. Ridges that are perpendicular to these westerly winds may have considerably higher wind energy flux than exposed flat areas.

#### CONCLUSION

Described above are some of the ways in which information in the regional wind energy resource atlases can be put to use to evaluate various aspects of an area's wind resource. One key point which we



have tried to emphasize in this paper is the importance of properly interpreting the wind resource maps and other information in the atlases. The wind resource maps alone are not adequate for an evaluation of an area's wind resource. The user should be aware of those areas where the resource estimates serve as only rough indicators (low certainty ratings). Additionally, the user should be aware that the map assessment values only refer to the fraction of land area in each land-surface form that is considered to be well exposed to the wind. We recommend that these various components of the resource assessment be considered together for a more thorough investigation of an area's wind resource. Use of grid cells on most of the maps in the atlas should make it easy for the user to locate his area and transfer the information conveniently from one map to the other. Any comments or suggestions on the information given in the wind resource atlases and the presentation of this information would be kindly appreciated by the author.

#### ACKNOWLEDGMENT

The author gratefully acknowledges the following for their assistance:

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## QUESTIONS AND ANSWERS

D. L. Elliott

From: Mr. Iriarte

Q: Why are calculations and measurements not references to 30 m in the atlases?

A: *The two reference heights of 10 m and 50 m were chosen to bracket typical application heights for the assessment. Adjustment to other heights is a straight forward application of a power law.*

From: Anonymous

Q: How did you apply the  $1/7$  power law in extrapolating the data to nearby areas or to areas outside the grid cell in which the data were located?

A: *The  $1/7$  power law was used to adjust observed wind speeds ( $3/7$  for wind energy flux) to the 10 to 50 m reference height from the given anemometer height for each station. No fixed extrapolation model was used to project the values from a sheltered site to an exposed site. This was done subjectively using guidance from stations at exposed locations and, most often, topographical indicators.*

From: B. Liebowitz

Q: How was the upper-air data extrapolated downward?

A: *Upper-air wind speed climatologies and for the 850, 700 or 500 mb levels were extrapolated linearly to representative ridge top elevations in each grid using the mean heights for these pressure levels in each grid cell. The extrapolation provided a mean free-air wind at ridge top height. One-third of the equivalent Rayleigh distribution free-air wind energy flux was then considered to represent the 10 m wind resource at the ridge top.*

From: H. J. Stewart

Q: What rules did you use for the high speed end in estimating average power density?

A: *For stations with digitized data, no limit was placed on an acceptable upper speed. For stations with summarized data, a wind speed only slightly higher (1 or 2 mph) than the low speed end of the upper wind speed class was used in the power density calculation.*

D. L. Elliott (continued)

From: S. Frandsen

Q: How good a fit was the Rayleigh distribution as used in the wind atlases? Did you consider using the Weibull distribution?

A: *At most inland sites with wind speeds averaging in excess of 4.5 m/s the Rayleigh distribution adequately represented the frequency distributions. At a few inland areas with a peculiar wind resource (e.g., San Geronio), at some coastal sites, especially in the trade wind latitudes, and at many island locations, the Rayleigh did not fit well. In some of these cases much improved fits could be obtained using the Weibull distribution. However, in the resource assessments analytical distributions were used where only mean wind speed data were available; and in this case the Rayleigh version of the Weibull was used to estimate the wind energy flux.*

From: L. I. Szabo

Q: What is the complete title of these wind atlases and where can they be obtained?

A: *Wind Energy Resource Atlases are available for each of 12 regions of the United States and its territories from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC.*

From: J. W. Snow

Q: Are the assessments contained in the atlases based upon data, i.e., "measurements" only? Have any areal distributions suggested by numerical simulations of the wind been incorporated?

A: *Measured wind data provides the backbone to the assessments. Projection of these data to exposed sites was guided by information from topographical indicators and the results of numerical and physical modelling (where available). No specific modelling efforts were undertaken to support the resource assessments.*

Q: Does PNL consider its atlas series as a "preliminary" assessment at the size scale of about 25 x 25 km?

A: *It is not preliminary in the sense that a follow-on series is anticipated. But it is preliminary in the sense that verification studies will shed light upon the accuracy and detail of the assessments at this scale.*

# APPROACHES TO WIND RESOURCE VERIFICATION

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Pacific Northwest Laboratory  
Richland, Washington 99352

## ABSTRACT

Verification of the regional wind energy resource assessments produced by the Pacific Northwest Laboratory addresses the question: Is the magnitude of the resource given in the assessments truly representative of the area of interest? Approaches using qualitative indicators of wind speed (tree deformation, eolian features), old and new data of opportunity not at sites specifically chosen for their exposure to the wind, and data by design from locations specifically selected to be good wind sites are described. Data requirements and evaluation procedures for verifying the resource are discussed.

## INTRODUCTION

Wind energy resource assessments have been completed for 12 regions of the United States and its territories. These assessments are based primarily on readily available, summarized, near-surface wind data; upper air data contributed to the assessments in mountainous areas. Annual and seasonal average wind energy flux (wind power class) is given for sites which are well exposed to the wind. Figure 1 shows those areas of the country with a wind resource of  $\geq 300$  W/m<sup>2</sup> at 50 m. However, in many areas of the country only a small percentage of the stations used in the assessment could be considered to be representative of well-exposed sites.

An estimate of the degree of certainty associated with the resource assessment was made. Assignment of a certainty rating was based on the availability of data in well-exposed locations, the complexity of the terrain, and the expected geographic variability of the resource. Certainty ratings of 1 or 2, shown in Figure 2 for the 48 conterminous states of the United States, indicate that little quantitative data is available in that area, that the complexity of the terrain makes the available data unrepresentative of well-exposed locations, or that the wind resource may vary greatly over small distances. Areas with low resource certainty are candidates for verification.

POWER CLASS 3 OR HIGHER

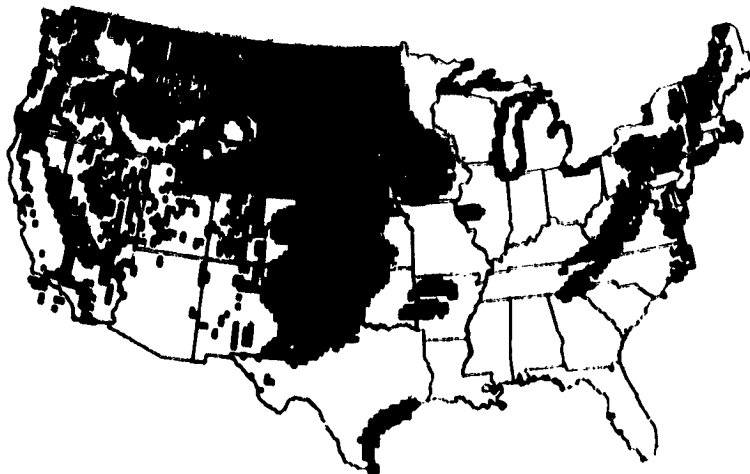


FIGURE 1. AREAS OF THE CONTERMINOUS 48 UNITED STATES WITH A WIND ENERGY FLUX  $\geq 300$  W/m<sup>2</sup> AT 50 m ABOVE THE GROUND

CERTAINTY RATINGS 1 AND 2



FIGURE 2. AREA OF THE CONTERMINOUS 48 UNITED STATES WITH A LOW OR LOW-INTERMEDIATE (2) RESOURCE CERTAINTY RATING

But, a low certainty rating alone is not a sufficient reason for conducting verification activities. Other factors related to the wind resource will likely enter into a decision on verification. For example, in areas with low wind energy potential (say, less than  $300$  W/m<sup>2</sup> at 50 m), in areas with low present costs of energy, or in areas with no apparent markets for wind energy, there is likely to be no urgency for verification activity.

In this paper several approaches to conducting resource verification will be discussed. These approaches mainly address the question: Is the magnitude of the wind resource given in the regional wind energy resource assessments truly representative of the area of interest?

Verification activities could also be designed to answer other questions about the resource. For example, is the areal distribution of the wind resource representative of the area of interest? The latter question is much more difficult to answer than the former. A measure of the wind resource at specific sites will suffice to answer the question on magnitude but an extremely large number of measurements would be needed to effectively verify the areal distribution. In fact, numerical modeling may be the only tractable approach to verifying the areal distribution estimates.

## APPROACHES

All approaches to verification of resource magnitude rely on the availability of wind data. This data may be qualitative, i.e., the result of the analysis of some indirect indicator of wind speed such as the deformation of trees or quantitative, i.e., the result of a wind measurement program, using data of opportunity or data by design.

### Qualitative

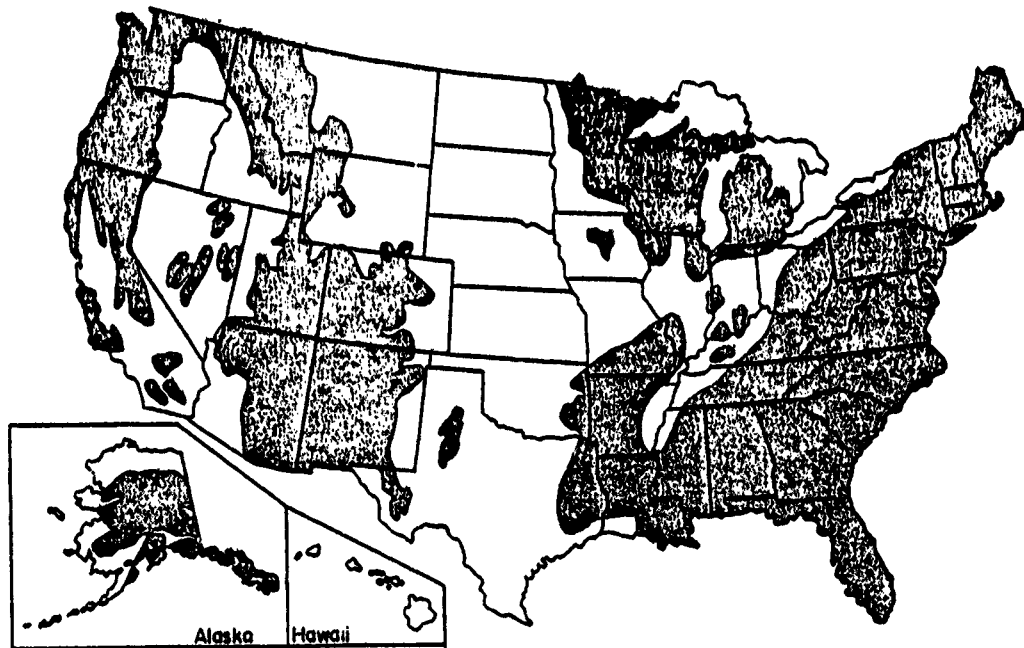
Qualitative approaches to resource verification depend on the presence of indicators of wind speed such as wind deformed vegetation and evidence of wind erosion. Techniques have been developed for estimating mean annual wind speed from wind-induced tree deformation [1,2]. Figure 3 shows the distribution of tree species (pines, hemlock, spruce, Douglas fir, and firs) for which the extent of wind-induced deformation has been calibrated in terms of the annual mean speed. These calibrations have been developed from data obtained mainly in the Pacific Northwest and the Northeast; similar species growing in other areas may not respond to the wind in an identical fashion.

In areas of the country in which wind erosion helps shape the landscape, certain eolian features such as sand dunes, wind scour streaks and playas may be useful indicators of wind energy potential. Figure 4 shows areas of the 48 conterminous United States that may be susceptible to wind erosion [3]. Techniques have been developed for estimating wind speeds from sand dunes and other eolian features [4].

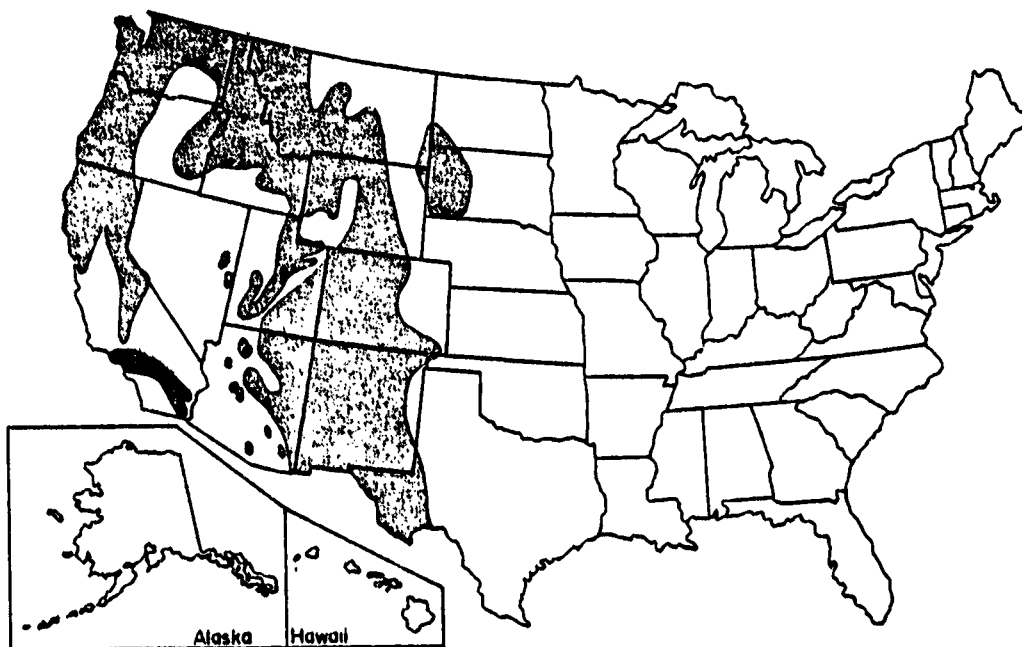
Qualitative approaches to wind resource verification are likely to be labor-intensive and to require personnel with expertise in biology (dendrology) and geology (geomorphology) as well as meteorology. Preliminary studies of satellite imagery and high altitude aerial photography may be needed to identify promising locations for more detailed study. Field observation programs may then be conducted in the promising locations to obtain data on tree deformation or eolian features. Post-field-program analysis will then be needed to convert these data to equivalent wind speeds.

Given the presence of suitable biological or geological indicators, this approach to verification could be carried out in a period of several months over an area of several hundred square miles. Point estimates of wind speed would likely be obtained for many locations

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THE DISTRIBUTION OF PINES, HEMLOCK AND SPRUCE  
IN THE UNITED STATES.



THE DISTRIBUTION OF DOUGLAS-FIR AND PONDEROSA  
PINE IN THE UNITED STATES.

FIGURE 3. THE RANGE OF SPECIES OF PINE, HEMLOCK, SPRUCE AND  
DOUGLAS FIR IN THE UNITED STATES [1]



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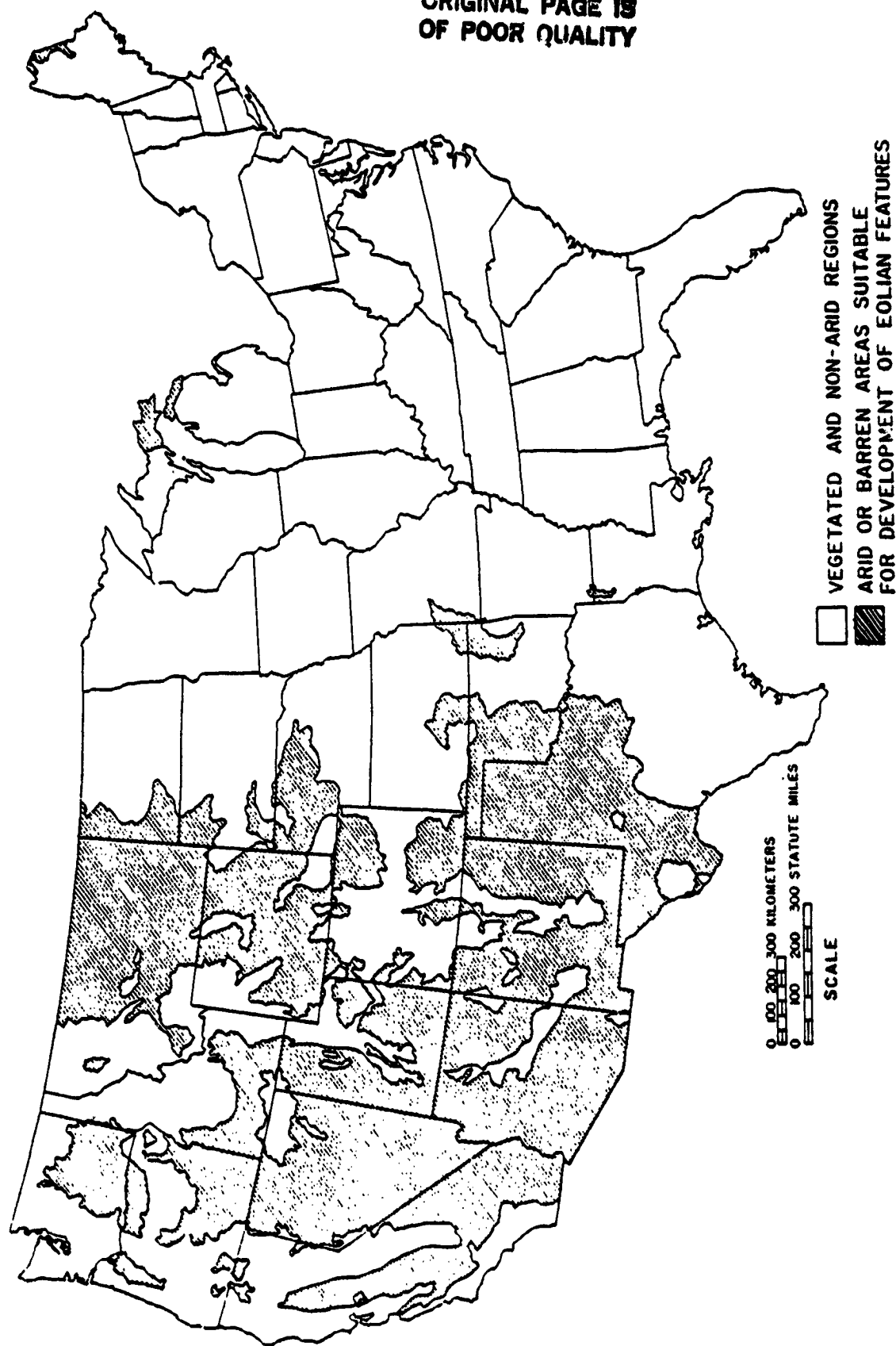


FIGURE 4. BARREN AND ARID AREAS OF THE 48 CONTERMINOUS UNITED STATES [3]

that meet the criterion of good wind exposure. The accuracy of the resulting verification is dependent on the accuracy with which indirect indicators can be converted to wind speeds.

### Data of Opportunity

The wind resource assessments available today are based primarily on "data of opportunity", that is, data taken for purposes other than wind energy prospecting or monitoring. As a result the location of such stations is generally quite different from the optimal wind energy site that is well exposed to the wind in an area of low surface roughness and with no nearby obstacles.

At present existing quantitative methods do not reliably convert wind data obtained at a less than optimally situated site to what it would be at the optimal site. The approach taken by PNL is to first become as familiar as possible with the topographic setting and exposure of each station. The weather patterns that affect each location and their influence on the wind resource are thoroughly examined. Then the wind resource at exposed locations is estimated by subjectively extrapolating the available data. In this extrapolation those sites with the best wind exposure are given greatest weight.

In some areas, especially in terrain of large vertical relief, the data of opportunity are supplemented with upper-air wind climatologies. Vertical extrapolation techniques are applied to estimate the free-air wind resource at mountain-top and ridge-crest levels. Estimates of the ridge crest or mountain summit wind resource are guided by both the upper-air extrapolation and available surface data of opportunity.

In a program of wind resource verification in which data of opportunity are the principal source of quantitative information, extrapolation techniques similar to these will have to be applied. In this case the verification information may be subject to the same uncertainties as the resource assessment being verified. Nevertheless, if the two estimates of the resource magnitude are based on independent data sets and are in agreement, a significant increase in credibility of the resource magnitude will have been achieved.

Where are these data of opportunity to be found? The regional resource assessments made use of data that had been archived by the National Climatic Center, either in time series form in the TD1440 tape series, or as wind summaries [5]. Wind data from other sources such as electric utilities, nuclear power plants and research projects were used in the resource assessments whenever they were already summarized. The Wind Energy Resource Atlases provide the location of stations used in each regional assessment. Additional data of opportunity, not used in the regional assessments, are available from the NCC for many stations for which the data have not been summarized or digitized [6]. Many colleges and universities, electric utilities, consulting meteorologists, state highway departments, state departments of natural resources, other government agencies, etc., have wind data in unsummarized form (e.g., strip charts, magnetic tape, log books) or as

summaries not used in the regional assessments which may be suitable for resource verification. Locating, reducing and analyzing these data for resource verification will be a major undertaking.

The data of opportunity so far discussed have been previously taken and archived; they are old data. However, new data of opportunity are now being taken at many sites across the country. Much of these data will have a short life time because the data are being used for real-time monitoring rather than for obtaining a climatological record. Therefore, tapping these sources of data will require that: 1) the organization responsible for collecting this data be made aware of the usefulness of their data for wind energy purposes; 2) an arrangement be made whereby the wind data are in some way retained or made accessible for retrieval by someone else; and 3) the data be collected or retrieved by those doing the resource verification in a timely and routine manner.

A number of federal and state agencies presently make use of the Geostationary Operational Environmental Satellite (GOES) Data Collection System (DCS) to telemeter data from remote sites to the National Earth Satellite Service (NESS) computer in the World Weather Building in Marlow Heights, Maryland [7]. Data received by NESS are archived for at least 24 hours and can be made available to parties other than the original user upon request. Access to the data in the computer can be via dial-up modem or direct line [8]. It is also possible to receive the telemetry signals directly from GOES with an appropriate ground receiving station.

Some of the federal and state users of GOES-DCS [9] are:

U.S. Department of Interior Bureau of Land Management	Mr. Dale Vance Office of Scientific Systems Development (303) 234-4620
U.S. Department of Interior Bureau of Reclamation	Mr. Donald Rottner Office of Atmospheric Resources Management (303) 234-3901
State of California Department of Forestry Department of Water Resources	Mr. Larry A. Mertens Department of General Services (916) 445-2034
State of Washington Department of Natural Resources	Mr. James B. Tucker (206) 753-5350
U.S. Department of Agriculture Forest Service	Mr. John Warren (208) 384-1439

Each of the GOES-DCS users listed above collects wind data along with other parameters and has expressed a willingness to share this data with other interested parties. Because the data sent through the

GOES-DCS may not be in engineering units, it will be necessary to obtain calibration equations or tables from the organization operating the remote telemetry platform.

The use of data of opportunity in resource verification has the advantage that data over long periods of record can be used and that the expense of procuring, installing and operating a wind measurement system are avoided. However, the disadvantage is the lack of control over the location of the station and the quality of the data.

### Data by Design

In contrast to data of opportunity, data by design refers to a measurement program specifically designed to meet the needs of resource verification. Such a measurement program should encompass activities such as anemometer site selection and acquisition, measuring system procurement, calibration and installation, data retrieval, and data processing. This approach to resource verification will involve an investment in hardware (the measuring system and processing equipment) as well as labor (siting, calibration, installation, maintenance and data processing).

Site selection is very important to the verification of resource magnitude. Since the assessments give the resource at locations well exposed to the wind, proper verification depends on selecting sites that meet this criterion. Siting guidelines similar to those needed for siting wind turbines [10,11] should be followed for selecting the anemometer sites. Preliminary site identification may be made from an analysis of topographic maps of the area of interest. Field inspection of these sites must follow to further refine the selection.

At this point the access to desirable sites may be an issue. Ownership of or jurisdiction over each site may need to be determined and permission for access to and installation of the anemometer may have to be obtained. Permission for access may be needed even for the field inspection activity.

Some resource verification activities have operated on the principal of data by design at locations of opportunity. Most anemometer loan programs operate in this mode. By a careful screening of applicants to a loan program, sites suitable for resource verification can be located if the loan program is widely advertized.

Towers in microwave communication networks also present sites of opportunity for resource verification. Very often the towers are located on ridge crests or hilltops, which may be representative of sites well exposed to the wind. Microwave communications towers offer another advantage in that it may be possible to use the communication system to telemeter the wind data to a central facility for archiving and processing.

The selection of a wind measuring system will depend on the end-use of the wind data. For verification of the magnitude of the wind

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resource, the minimum that must be measured is the wind speed. However, if it is desirable to have a more complete understanding of the nature of the resource at the verification point, wind direction should also be measured.

Wind-run anemometry over long time periods will provide a measure of the mean wind speed, but not the wind energy flux. As the frequency of reading the wind run increases, the detail about the wind resource will improve. Measurement strategies that provide frequent (more than one per day), uniformly spaced samples of wind speed are desirable [10]. However, other measurement strategies employing intermittent or random sampling may also be applicable [12,13].

Wind measuring systems chosen for resource verification need to be highly reliable and durable. High sensitivity to low wind speeds or to rapid wind fluctuations is not needed for this task. Onsite data storage should, as a minimum provide speed (and direction, if included) frequency of occurrence information. However, if the labor for analysis is available, strip chart recordings of speed (and direction) will suffice. Wind sensors should be positioned no less than 10 m (33 feet) above the ground and even higher in locations surrounded by tall vegetation. Other references to wind measuring systems and measurement strategies may be found in the sources listed in the Solar Energy Research Institute's Wind Energy Information Directory [14].

In any extensive measuring program an effort to ensure the quality of the data is essential to success. Procedures for routine calibration of equipment prior to installation and at regular periods thereafter provide for user confidence in the data. This opportunity for quality control is not available when using data of opportunity.

#### VERIFICATION

Data processing needs for resource verification are modest. The quantity to be calculated and compared to the resource assessment is the wind energy flux (WEF), also called the wind power density:

$$WEF = \frac{1}{2} \rho V^3$$

where  $\rho$  = air density in  $\text{kg/m}^3$   
 $V$  = wind speed in  $\text{m/s}$

so that the WEF is in  $\text{W/m}^2$ . To compute the average WEF over a long period of time requires calculating the mean of the cube of the wind speed,  $\overline{V^3}$ , and estimating the mean air density. The mean air density ( $\rho$ ) can be estimated from climatic information and the station elevation.  $\overline{V^3}$  can be calculated from different types of data:

$$\overline{V^3} = \frac{1}{N} \sum_{i=1}^N V_i^3 = \sum_{j=1}^C f_j V_j^3$$

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where  $V_1$  = the 1<sup>th</sup> wind speed obtained from a time series record (e.g., strip chart) that contains N readings, or

$V_j$  = the midpoint of the j<sup>th</sup> wind speed bin in a speed frequency distribution for which

$f_j$  = the frequency of occurrence of wind speeds in the j<sup>th</sup> bin.

Now the mean wind energy flux is

$$\overline{WEF} = \frac{1}{2} \rho \overline{V^3}$$

If, however, only mean wind speed is available, such as that obtained from a wind run anemometer (wind odometer) then an assumption about the distribution of speeds about the mean speed must be made to arrive at  $\overline{V^3}$ . A study of 140 stations, showed that the wind speed distribution can be adequately described for most locations with a Weibull distribution [15]. From the information presented in [15],  $\overline{V^3}$  can be approximated from  $\overline{V}$ .

A final adjustment to the mean wind energy flux may be needed to scale the measured (calculated) value to the same reference height (10 or 50 m) used in the wind resource assessments. Standard practice in the resource assessments was to scale the wind energy flux to 10 or 50 m using a 3/7 power law (equivalent to 1/7 law for speed):

$$\overline{WEF}_R = \overline{WEF}_Z \left( \frac{Z}{Z_R} \right)^{3/7}$$

where  $\overline{WEF}_Z$  = the mean wind energy flux at the anemometer,

$Z$  = the height of the anemometer above ground in meters and

$Z_R$  = is the reference height of 10 or 50 m.

If the mean wind energy flux so calculated falls within the range of the wind power class given for that location in the resource assessment atlas, the resource has been verified. Departure of the measured value by more than one power class from the assessment could mean

- a) that the assessment is incorrect, or
- b) that the verification site is really not representative of the typical well exposed site for that terrain type. This situation may be the case if the verification value is less than the assessment.
- c) that the period on which the verification is based is not representative of the long term climatological mean for that location. This may be especially applicable to verification's based on data obtained over a period of one year or less.

The author would be pleased to hear about any resource verification activities in progress and, of course, the results of the verification.

#### ACKNOWLEDGMENTS

This work has been supported by the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

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QUESTIONS AND ANSWERS

W. R. Barchet

From: Mr. D'Aquanni

Q: Does the certainty index reflect poorly exposed sites?

A: Grid cells which contained sites with poor wind exposure were given a lower certainty rating than grid cells with sites that are well exposed.

From: A. Jagtiani

Q: Over what period of time should wind data be collected for an area to verify the power class?

A: For the purpose of assessing the resource, periods of record less than one full year are considered inadequate. Present statistical guideline is that mean wind speeds derived from data from a full annual cycle will be within 10% of the long-term mean 90% of the time. A longer period is needed for the same confidence and accuracy for wind energy flux.

Q: How do you compute the power density for a specific site?

A: The exact mathematic expression depends on the form of the data available from the site. For time series data the mean wind energy flux (WEF) is

$$\overline{WEF} = \frac{1}{2N} \sum_{i=1}^N \rho_i V_i^3 \text{ or } \frac{\bar{\rho}}{2N} \sum_{i=1}^N V_i^3$$

where  $\rho_i$  and  $V_i$  are the air density and wind speed for the  $i^{th}$  reading out of a total of  $N$  readings. If density is not measured a mean density ( $\bar{\rho}$ ) estimated from the site climatology and elevation can be used. For frequency distribution data the WEF is

$$\overline{WEF} = \frac{1}{2} \bar{\rho} \sum f_j V_j^3$$

where  $f_j$  is the frequency with which speeds in the  $j^{th}$  speed category are observed and  $V_j$  is the mean speed associated with the  $j^{th}$  class.

If only a mean wind speed is available for the site an analytical speed distribution can be used to estimate the WEF. For the Weibull distribution this reduces to:

$$\overline{WEF} = \frac{1}{2} \bar{\rho} \frac{\Gamma(1 + 3/k)}{[\Gamma(1 + 1/k)]^3} \bar{V}^3$$

W. R. Barchet (continued)

where  $k$  is the Weibull shape parameter. For a Rayleigh distribution this becomes

$$\overline{WEP} = \frac{1}{2} \rho (1.91) \bar{V}^3$$

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ASSESSING THE REPRESENTATIVENESS OF WIND DATA  
FOR WIND TURBINE SITE EVALUATION

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and

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ABSTRACT

Once potential wind turbine sites (either for single installations or clusters) have been identified through siting procedures, actual evaluation of the sites must commence. This evaluation is needed to obtain estimates of wind turbine performance and to identify hazards to the machine from the turbulence component of the atmosphere. These estimates allow for more detailed project planning and for preliminary financing arrangements to be secured. The site evaluation process can occur in two stages: 1) utilizing existing nearby data, and 2) establishing and monitoring an onsite measurement program. Since step (2) requires a period of at least 1 yr or more from the time a potential site has been identified, step (1) is often an essential stage in the preliminary evaluation process. Both the methods that have been developed and the unknowns that still exist in assessing the representativeness of available data to a nearby wind turbine site are discussed in this paper. This paper then discusses how the assessment of the representativeness of available data can be used to develop a more effective onsite meteorological measurement program.

1.0 INTRODUCTION

Successful site selection activities, described in another paper at this conference [1], should lead to the identification of one or more "candidate" turbine or turbine cluster installation sites. Once these candidate sites are identified, evaluation of the wind characteristics at the sites must commence to allow for project planning and for preliminary financing arrangements. This paper discusses our current state

of knowledge of the site evaluation process as it relates to installation of large machine clusters, and points out areas where additional work is required.

In general, candidate sites will not have sufficient onsite documentation of wind characteristics to be completely adequate for planning the installation. The developer of the installation must then make use of existing data sources, and determine the representativeness of those data to the candidate sites. A number of techniques may have to be applied, including numerical simulations, statistical procedures, and even subjective judgment, to estimate the wind characteristics at the candidate sites. These estimates may give early information on the projected performance of a turbine or turbine cluster at the candidate site; although the lack of onsite information will probably mean that the developer can not place the highest possible confidence on the performance projections. In addition, there may be certain turbulent characteristics of the atmosphere at the candidate site that only an onsite measurement program could identify adequately.

Another important reason for the developer or planner to assess the representativeness of existing data to a candidate site is that a more intelligent and cost-effective onsite measurement strategy can be developed. In some cases, nearby data may be sufficiently representative to eliminate the need for onsite measurements at all; in other cases, an extensive measurement system (including multiple towers if it is a large cluster site) may be necessary before sufficient information can be derived from a site to allow the project to proceed.

Basically, the following must be taken into consideration in assessing the representativeness of an existing data set to a nearby candidate site:

1. The degree to which the data represents the interannual variability of diurnal, seasonal, and annual wind statistics at the site.
2. The degree to which the data represents actual conditions at the site given geographical and topographical variability between the data source and the site.
3. The degree to which there would be impacts on the representativeness of existing data occurring due to modifications in the lower atmospheric boundary layer as a result of an installation of a large cluster of turbines.

The focus of the first section of this paper is on (1) and (2); understanding of (3) is very limited at present and should be a major thrust of research in the future. Following this first section, the results of recent research in determining the most appropriate onsite measurement strategy for site evaluation will be presented.

## 2.0 DETERMINING THE REPRESENTATIVENESS OF EXISTING DATA SETS

### 2.1 Climatological Adjustment of Short-Term Data

In many cases, decisions to develop a wind turbine project will have to be based on the existence of wind data that covers only a short period of time. The data may have been collected by the developer of the wind project, so that most likely there would not have been time to wait until a full climatology of the wind characteristics at the site has been established. In other cases, nearby data collected for some other purpose may be available, but again will not have had sufficient length of record to discern interannual variability. Since the wind project developer, as well as finance institutions that provide the developer with working capital, need to know variations in year-to-year cash flow that the project will experience, and in particular need to be aware of potentially serious cash flow situations that would occur during one or several consecutive low-wind years, knowledge of the interannual variability is extremely important in the planning stages of a project.

A number of studies have been made to adjust short-term measurements to long-term climatological values. These studies include statistical procedures for relating short-term data to long-term records that are near the site, such as National Weather Service stations, time series analysis of short-term data in comparison with nearby long-term weather records, studies of synoptic climatology patterns, and use of numerical models.

#### 2.1.1 Wind Variability Statistics

Extensive research into using statistical and time series procedures for determining the representativeness of short-term to long-term (e.g., 30 yr) means, and the variance of the mean has been made [2,3,4, 5,6]. These studies are summarized by Hiestler and Pennell [7].

Corotis [5], for example, assesses the reliability of a computed mean speed with a confidence interval. If  $\bar{V}$  and  $\sigma_V$  are the computed mean and hourly standard deviation of wind speed for a period of time, such as a season or a year, then there is a probability of  $(1-\alpha)$  that the true long-term mean wind speed for that period of time is bounded by:

$$\text{Probability} = \bar{V} \pm k_{\alpha/2} \sigma_V / \sqrt{n} \quad [1]$$

where  $k_{\alpha/2}$  is the standard normal deviate evaluated at a cumulative level of  $(1-\alpha/2)$ , and  $n$  is the number of equivalent independent hourly readings on which  $\bar{V}$  is based. Values of  $k_{\alpha/2}$  are readily available from standard statistics textbooks. This study, as well as others referenced above, all conclude that the following general guideline applies: "...the climatic mean wind speed will be within  $\pm 10\%$  of a single mean wind speed observation with about 90% confidence." In general, this same guideline applies to a single season of measurements being within  $\pm 10\%$  of the climatic seasonal average with 90% confidence.

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Obviously, this guideline does not apply to all sites. In fact, the accuracy of the estimate at any given site depends on the coefficient of variation of the site annual mean wind speed  $\sigma_a/\bar{V}$ , where  $\bar{V}_a(a)$  is the climatic mean and  $\sigma_a$  is the standard deviation of annual means. Information on how  $\sigma_a/\bar{V}_a$  can provide more precise error ranges on a long-term estimate from a single monthly or annual value is demonstrated in [3]. Figure 1 shows their results of the average distribution of monthly and annual wind variations for a survey of 40 National Weather Service stations. This figure shows that on the average a single observation of annual mean wind speed falls within the interval of approximately  $0.8 \bar{V}$  and  $1.16 \bar{V}$  with 90% certainty. They then looked at the distribution of  $\sigma_m/\bar{V}_m$  for monthly values and  $\sigma_a/\bar{V}_a$  for annual values. The variability distributions of various percentiles of  $\sigma/\bar{V}$  values are shown in Figure 2 (for annual) and Figure 3 (for monthly). Thus, for sites where it is assumed extreme variability occurs, the 90 percentile  $\sigma/\bar{V}$  values would be within about  $\pm 15\%$  of a given single annual or  $\pm 18\%$  of a monthly value.

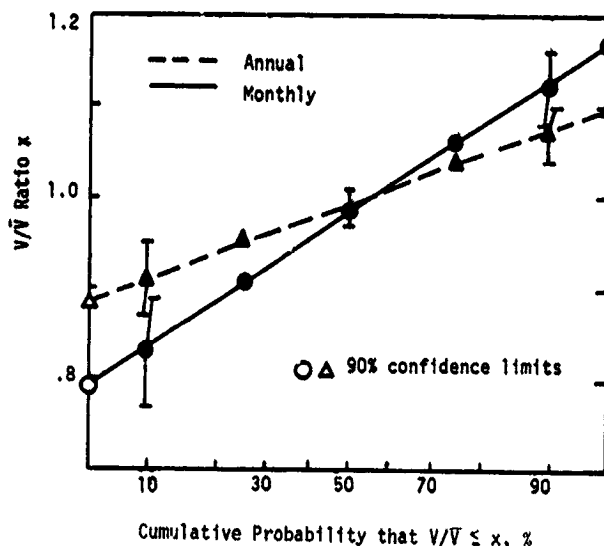


FIGURE 1. AVERAGE DISTRIBUTION OF MONTHLY AND ANNUAL MEAN WINDS ABOUT THE LONG-TERM MEAN (FROM [3])

This information is also important in developing an onsite measurement strategy which can give an indication of the long-term mean using only intermittent measurements. These strategies will be discussed in Section 3.2.1.

#### 2.1.2 Climatological Adjustment Using a Reference Station

A number of attempts have been made to develop reliable techniques for adjusting short-term (season or year) data to climatological values by

(a) In this report, subscript "a" refers to annual values, and subscript "m" refers to monthly values.

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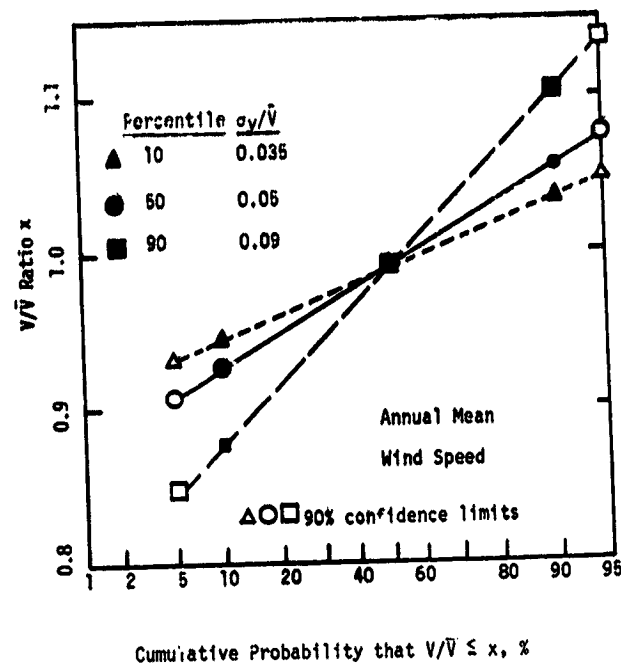


FIGURE 2. AVERAGE DISTRIBUTION OF ANNUAL-MEAN WINDS ABOUT THE LONG-TERM MEAN FOR VARIOUS  $\sigma/V$  VALUES, ASSUMING A GAUSSIAN DISTRIBUTION OF  $V/V$  (FROM [3])

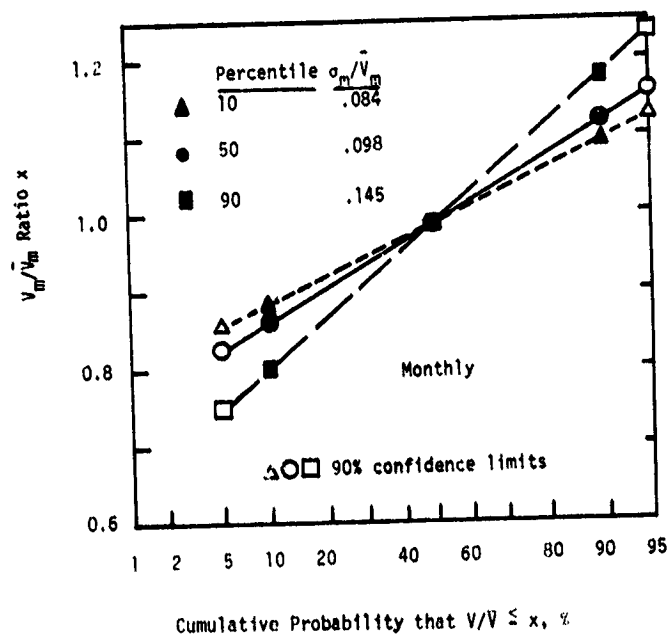


FIGURE 3. AVERAGE DISTRIBUTION OF MONTHLY MEAN WINDS ABOUT THE LONG-TERM MEAN FOR VARIOUS  $\sigma/V$  VALUES, ASSUMING A GAUSSIAN DISTRIBUTION OF  $V/V$  (FROM [3])

comparison with nearby long-term data. These techniques range from evaluating the ratios of the data sets to applying statistical or time series climatological relations [8,3,5,9]. For example, Corotis [5] suggests use of the statistical relation:

$$\bar{V}_c = V_c - \rho(V_r - \bar{V}_r) \frac{\sigma_c}{\sigma_r} \quad [2]$$

where  $\bar{V}_c$  = estimated long-term mean at the candidate site

$V_c$  = observed mean at the candidate site

$V_r$  = observed mean at the reference site during the period of candidate site measurements

$\bar{V}_r$  = observed long-term mean at the reference site

$\rho$  = spatial cross-correlation between sites during period of candidate site measurements

$\sigma_c, \sigma_r$  = hourly standard deviations for candidate and reference sites, respectively.

However, because investigations have shown that monthly and annual cross correlations between nearby stations is relatively low, even in simple terrain, ample evidence exists to show that adjustment of annual or monthly mean wind speeds using relations such as (2) or the simple ratio method does not result in significant and reliable improvement in estimates of climatic means over using the guidelines presented in the previous section.

Recent and ongoing research show that synoptic climatology methods may also provide useful ways of characterizing short-term data sets to a long-term climatology. For example, Ossenbrugen et al. [9], in a study of offshore wind power potential, compared the 3-yr Boston Lightship records with the 31-yr Boston Logan Airport records by stratifying the latter into various categories of "wind seasons". By applying statistical tests between comparative data sets, and accounting for serial correlation between observations, the authors were able to adjust the Lightship data to the longer term Logan Airport data to within specified confidence limits.

## 2.2 Adjusting Nearby Data to a Site

### 2.2.1 Numerical Methods

In many cases, there will be no data available on the candidate site at all. This leaves the wind project developer with the dual problem of first interpolating nearby data to his site accurately, and then adjusting the interpolated values to long-term climatological statistics. Recently several studies were completed to produce methods of estimating



wind characteristics at a candidate site using only available nearby National Weather Service data [10,11,12,13]. These studies ranged from the application of sophisticated numerical objective analysis models to simpler interpolation techniques. All of the studies incorporated the effects of topography on wind flow between the National Weather Service stations and the site. Topography is incorporated in the numerical schemes by introducing topographic features on the computational grid and enforcing mass conservation in the calculations. The interpolation scheme is adjusted for topography by utilizing weighting factors.

A sample of the results of a test of one of the numerical methods is shown here. This method is an improvement of a modeling technique developed by Bhumralkar [13] following a concept of atmospheric flow modeling in the lower atmosphere developed by Sherman [14]. The details of the methodology and test procedure are described by Endlich et al. [15]. Basically, the model operates in a sigma coordinate system. The wind flow model is used to solve the continuity equation for each set of representative wind vectors (eigenvectors). A simulated wind history can then be produced at the candidate site, and from this simulation the statistics of the winds at the candidate site can be estimated.

The results of a test of the model at Clayton, New Mexico where nearby National Weather Service data is used as model input and compared with simultaneous wind measurements at the Clayton MOD-OA site is shown in Figures 4 and 5. Figure 4 gives a map of the location of the Clayton site, as well as locations of the available National Weather Service sites. Figure 5 gives comparisons of seasonal and diurnal values of simulations and observations.

In general, the simulated results are lower than observation for this case. Tests at other locations give similar results--only occasionally do simulations actually give higher statistics than observations. Despite these deficiencies, the simulations produce seasonal and diurnal patterns comparable with the observations. This does not necessarily occur at some of the more complex terrain sites, where National Weather Service stations are in valleys and candidate sites are on mountain tops. Nevertheless, modifications to this modeling scheme have produced improved results from earlier tests. This approach can be useful for estimating wind characteristics at a site with no known wind information. Results of these model applications should only be used as a means of providing preliminary guidance on the wind characteristics at a candidate site.

### 2.2.2 Use of Spatial Data Arrays

Suppose that some knowledge of the variance of wind speed is available in the region around a site, and that it is desirable to determine the representativeness of nearby data sets to a site. This type of information may be available, for example, if some preliminary site survey work had been done over the entire region in which the candidate site had been selected. Such data are often available in areas where a known resource exists and extensive measurements were established

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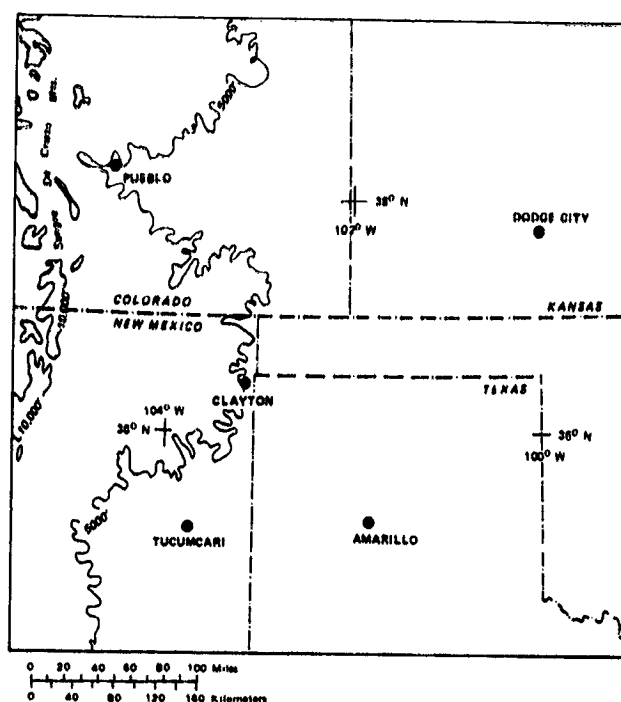


FIGURE 4. LOCATION OF THE CLAYTON, NM MOD-OA SITE AND NATIONAL WEATHER SERVICE STATIONS USED IN THE SRI MODEL (FROM [15])

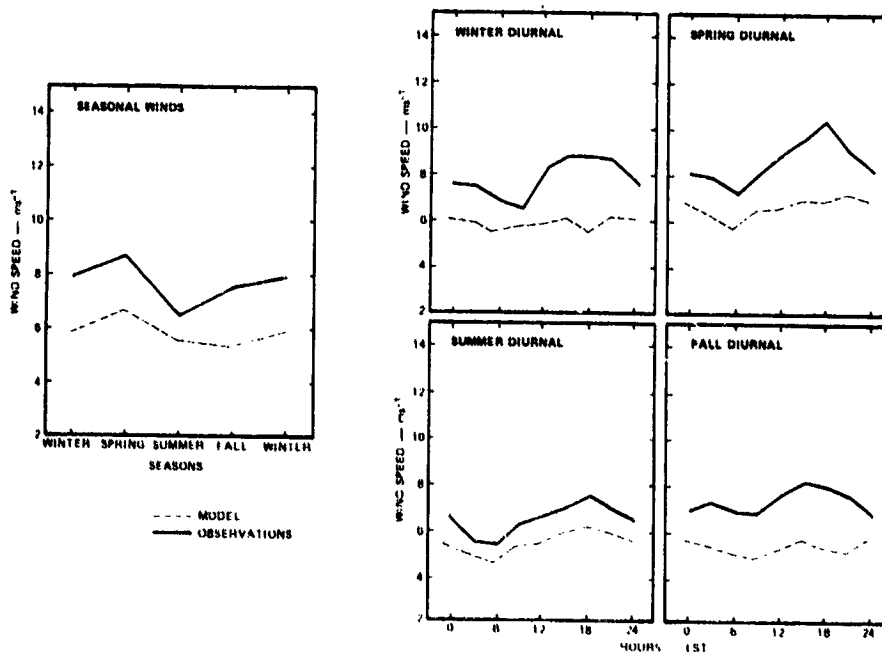


FIGURE 5. SEASONAL AND DIURNAL WIND SPEED CURVES FOR CLAYTON, NM AS SIMULATED BY THE SRI WINDFLOW MODEL AND AS MEASURED AT THE SITE (FROM [15])

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because of an interest in wind energy development. Under these circumstances the principles of Section 2.1.1 can be applied to establish confidence limits on the representativeness of a given data station to the site. Rewriting Equation [1]:

$$\bar{V}_s = k \left( \frac{\sigma_s}{\sqrt{n}} \right) \quad [3]$$

where  $\bar{V}_s$  = spatial average of mean wind speed values

$\sigma_s$  = standard deviation of individual site mean values to the spatial average.

The total standard deviation, accounting for spatial and temporal variability, is given by:

$$\sigma_T = \left( \sigma_v^2 + \sigma_s^2 \right)^{1/2} \quad [4]$$

Based on guidelines established from a survey of National Weather Service stations around the U.S. by Corotis [2]:

$$\sigma_v = \frac{0.1 \bar{V}}{k_{90\%}} \quad [5]$$

Then, for one year of measurements:

$$90\% \text{ confidence} = \bar{V} \pm 0.1 \left( \frac{\sigma_T}{\sigma_v} \right) \quad [6]$$

Thus, Equation [6] states that, in general, inclusion of spatial variability of mean wind speeds with climatological adjustment increases our uncertainty of the true long-term mean wind speed. Conversely, we have less confidence that the true long-term mean wind speed is  $\pm 10\%$  of the nearby measured mean winds.

For other confidence limits, [6] can be written in a more general form:

$$\text{Confidence interval (x)} = \bar{V} \pm 0.1 \left( \frac{\sigma_T}{\sigma_v} \right) \left( \frac{k_x}{k_{90\%}} \right) \quad [7]$$

### 3.0 ESTABLISHING A SITE MEASUREMENT STRATEGY

In the previous sections we have explored a number of techniques that can be used to estimate wind characteristics at a potential turbine or turbine cluster site where little or no onsite data exist. However, in many cases the information gained from employing these techniques is adequate only for initial planning purposes. It will not provide sufficient reliability or detail on wind characteristics at the proposed

site to complete detailed cluster design and to evaluate the economics of the cluster performance. Consequently, representative onsite measurements will still be required. In this section, we will explore factors that need to be considered for an effective onsite measurement strategy and review some recent research intended to shed a better light on a meaningful site evaluation process.

### 3.1 Current Site Evaluation Technology

In broad terms, a site evaluation strategy should be designed to build an information base on what is already known about a site. It should be structured to acquire needed information in a cost-effective and efficient manner. Guidelines have been published in documents such as siting handbooks [6,7], and experience is being gained through meteorological measurements at the Department of Energy's candidate site and turbine test site programs. The current strategy at DOE's candidate sites is described here as well as in reference [17].

Three levels of high response wind speed and direction cup-and-vane type sensors are installed on a 48.8-m guyed meteorological tower at heights of 9.1, 30.5, and 45.7 m. Although current technology is producing large wind turbines with heights considerably taller than these towers, the decision was made to install a shorter tower to conserve costs due to the large number of sites. (Currently, there are 34, including 6 with large wind turbines installed by DOE for field testing). Furthermore, it is assumed that the three levels of measurements will allow a reasonably accurate extrapolation of wind characteristics upward to a higher hub height. In addition, costs of purchasing, installing, and maintaining meteorological towers taller than 61 m (200ft) increase significantly because of FAA requirements to install safety beacon lights. Nevertheless, at a given site, a tower with sensors at hub height or above, particularly in areas of complex terrain, may well be worth the additional costs so that improved estimates of turbine or turbine cluster performance can be obtained.

At DOE's candidate sites, instantaneous samples of wind speed and direction are recorded once every 2 min on a digital cassette data logger. For most data loggers available on the market, this allows at least 2 wk of measurements to be made before the tape must be removed and replaced. Computerized monthly summaries of each site's wind characteristics are prepared from these cassettes. The summaries include such information as data recovery rates, mean wind speed and resultant wind direction for each level, peak gusts, diurnal wind characteristics, frequency distribution, power law coefficients by direction, and turbulent intensities.

### 3.2 Research on Alternative Measurement Strategies

#### 3.2.1 Intermittent Measurement Strategies

In cases where funds for site measurements are limited and numerous sites need to be evaluated, Ramsdell et al. [6] have investigated the

value of intermittent measurement strategies at a site, where measurement equipment would be installed for only a few months out of the year, and then reinstalled at other sites. The equipment would be rotated among the sites so that eventually all sites would have a few months of measurements each year. Such a strategy may be particularly significant for small machine applications, especially in cases where the time required to obtain sufficient measurements to have climatological significance is not critical.

The authors define a relative uncertainty as a way of relating short-term measurements at a site to long-term climatological averages. The relative uncertainty is the ratio of the standard deviations of estimates of long-term mean wind using individual monthly averages of a specific intermittent measurement strategy to that of a continuous measurement strategy. Based on an examination of 40 data sets, Figure 6 shows how the relative uncertainty decreases as the duration of monthly measurements increases. The figure shows that little reduction in uncertainty occurs beyond about 24 mo of measurements.

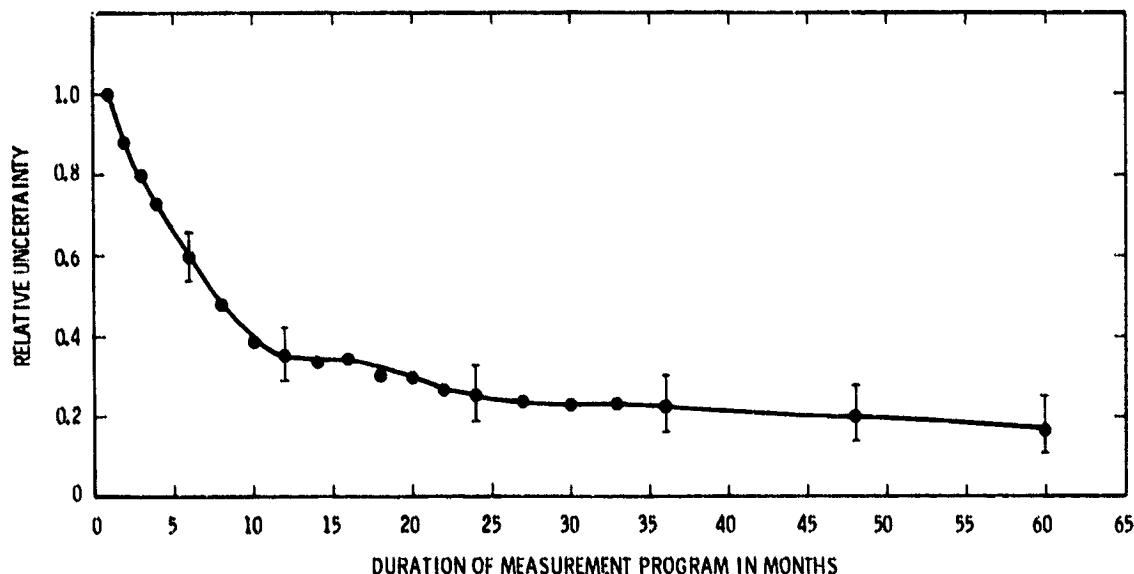


FIGURE 6. RELATIVE UNCERTAINTIES OF CONTINUOUS MEASUREMENT STRATEGIES ( FROM [6] )

Figure 7, also taken from Ramsdell et al. [6] shows how an intermittent measurement strategy can actually decrease the relative uncertainty of establishing a long-term climatology at the site. For an equal amount of time of equipment usage, the authors show that the samples obtained using an intermittent strategy are in essence independent, thus improving the certainty of having acquired a representative sample of data for establishing a long-term mean wind speed at the site. Of course, an intermittent strategy requires more actual time to develop a climatology. Thus, if an intermittent strategy is employed, Figure 6 shows that nearly twice the measurement period is required to obtain the same relative uncertainty than if a continuous strategy were used.

The study by Ramsdell et al. also confirms the conclusion of the climatological representativeness of short-term measurements discussed

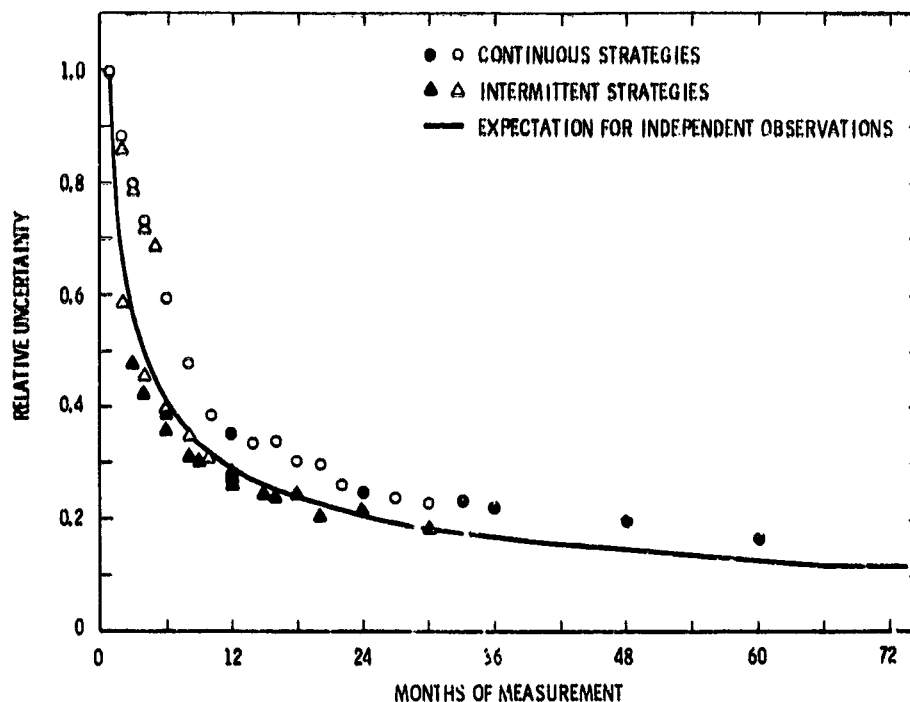


FIGURE 7. COMPARISON OF THE EFFICIENCIES OF INSTRUMENT USAGE IN CONTINUOUS AND INTERMITTENT MEASUREMENT STRATEGIES. OPEN SYMBOLS DENOTE STRATEGIES SHOWING TENDENCY TOWARD BIAS (FROM [6])

in Section 2.1.1. For the data sets used by the authors, a relative uncertainty of 0.35 for 12 mo of continuous measurements was obtained. Figure 8 gives the relationship between relative uncertainty and percent error in estimates of the long-term mean from their data. At a relative uncertainty of 0.35, the figure shows that there is a 90% confidence that the long-term mean wind speed is within  $\pm 10\%$  of the continuous measurements for 1 yr.

### 3.2.2 Site Evaluation at DOE's Turbine Test Sites

At the DOE MOD-OA 200 kW wind turbine test sites,<sup>(a)</sup> the meteorological towers that had been installed prior to the installation of the turbine for site evaluation purposes have been retained to support this phase of the research program. At each of the sites the towers are located less than 1 m from the turbine, and are situated such that they are measuring essentially the free-stream meteorological conditions at the site. Besides the routine measurement program discussed earlier, turbine output parameters are simultaneously recorded on the cassette data logger. These parameters include turbine electrical power output, nacelle yaw error, and wind speed and direction recorded from the

(a) Located at Clayton, New Mexico; Block Island, Rhode Island; Culebra, Puerto Rico; and Kahuku, Oahu, Hawaii.

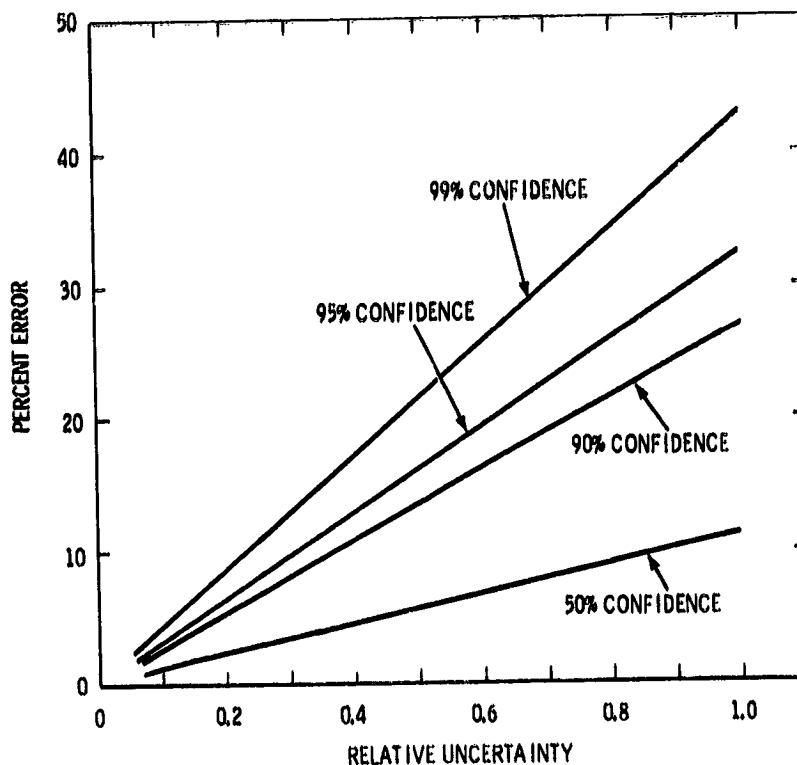


FIGURE 8. RELATIONSHIP BETWEEN RELATIVE UNCERTAINTY AND PERCENT ERROR IN ESTIMATES OF THE LONG-TERM MEAN (FROM [6])

nacelle anemometer. In addition, the data logger has the capability of recording short bursts of high frequency data ( $\sim 1$  sample/sec). This capability allows research into the most appropriate sampling strategy (average time per sample and frequency of samples) that should be undertaken as part of a site evaluation process at candidate sites.

Several hours of high speed data collected at the Clayton, New Mexico MOD-OA site on August 22, 1980 at a time when the turbine was operating between the cut-in and rated wind speed values is being examined as part of this site evaluation research effort. Preliminary results of this analysis are presented here to give an indication of the type of sampling strategy that might be appropriate at a site being considered for a turbine or turbine cluster installation.

Figure 9 shows the autocorrelation of 1-sec average values obtained from the three levels of the meteorological tower. In general there is an exponential decrease in autocorrelation with time between samples, occurring more rapidly at the lower levels where turbulent fluctuations in the surface layer due to friction are greater. As the correlation approaches 0, the samples become more and more independent. Since only independent samples enter into a climatological average, this figure implies that, when collecting instantaneous (i.e., 1-sec) samples to obtain a climatology of wind characteristics at a site, no more than

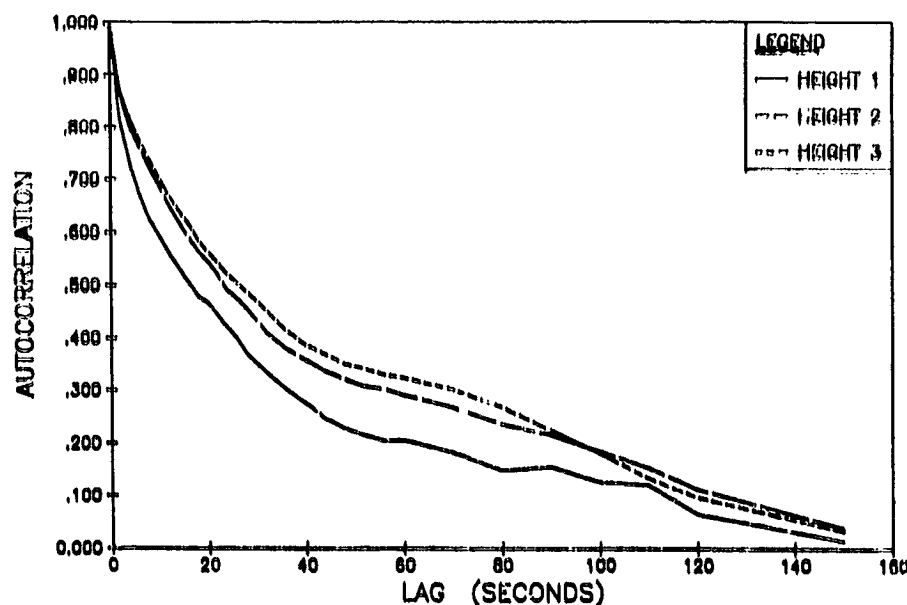


FIGURE 9. AUTOCORRELATION FOR 1-SEC AVERAGES OBTAINED FROM THREE LEVELS OF METEOROLOGICAL TOWER AT CLAYTON, NM, AUGUST 22, 1980. (NOTE: HEIGHT 1 = 10 m, HEIGHT 2 = 30 m, HEIGHT 3 = 50 m)

one sample per minute is necessary, and one sample every 2 min is adequate. This is comparable to the sampling strategy used at DOE's candidate sites.

As the sample averaging time is increased, the reduction in autocorrelation with lag time occurs at a slower rate. This is exemplified in Figure 10, which shows data from the 30-m level of the meteorological tower. The obvious conclusion from this figure is that a longer period of time between recording intervals is required as the averaging time increases to obtain independence between samples. It is interesting, however, that the autocorrelations converge at a sampling interval of 3 to 4 min, regardless of averaging time.

It is also of interest to examine cross correlation of measurements between the tower and the turbine parameters. Cross-correlation analysis sheds light on how various sampling strategies at the tower can explain variation of turbine power output. Figure 11 compares measurements at the 30-m level on the tower with measurements from the nacelle anemometer. The displacement in lag from the center of the figures shows the effect of travel time for small scale eddies from the tower to the turbine (the tower is approximately 100 m upwind of the turbine). As the averaging time increases, the cross correlation increases since smaller scale eddies are averaged out of the calculations. However, even for relatively long averaging periods, a perfect correlation is not obtained.

The same pattern is evident, but correlations are significantly lower, when the tower values are compared with turbine power output (Figure 12).



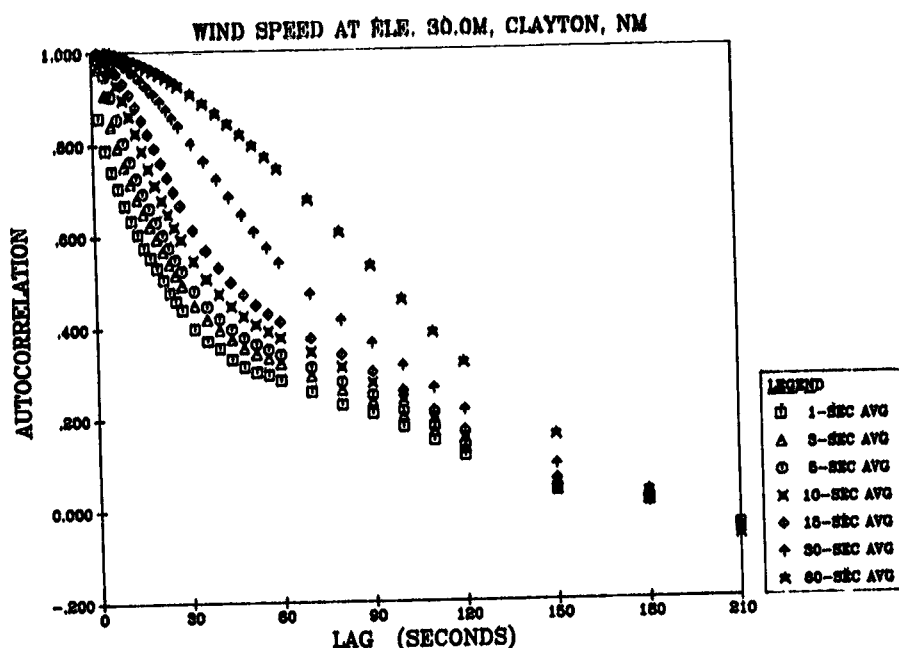


FIGURE 10. AUTOCORRELATION FOR VARIOUS AVERAGING INTERVALS AT THE 30-m LEVEL OF THE METEOROLOGICAL TOWER AT CLAYTON, NM, AUGUST 22, 1980

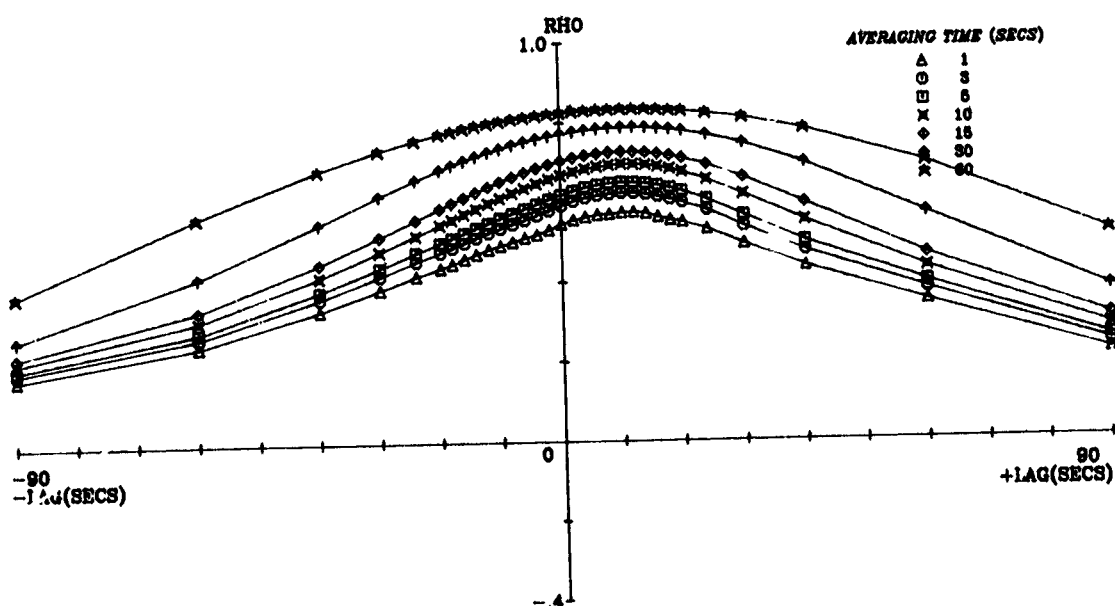


FIGURE 11. CROSS CORRELATIONS BETWEEN THE 30-m LEVEL OF THE METEOROLOGICAL TOWER AND THE MOD-OA NACELLE ANEMOMETER AT CLAYTON, NM FOR VARIOUS AVERAGING INTERVALS, AUGUST 22, 1980

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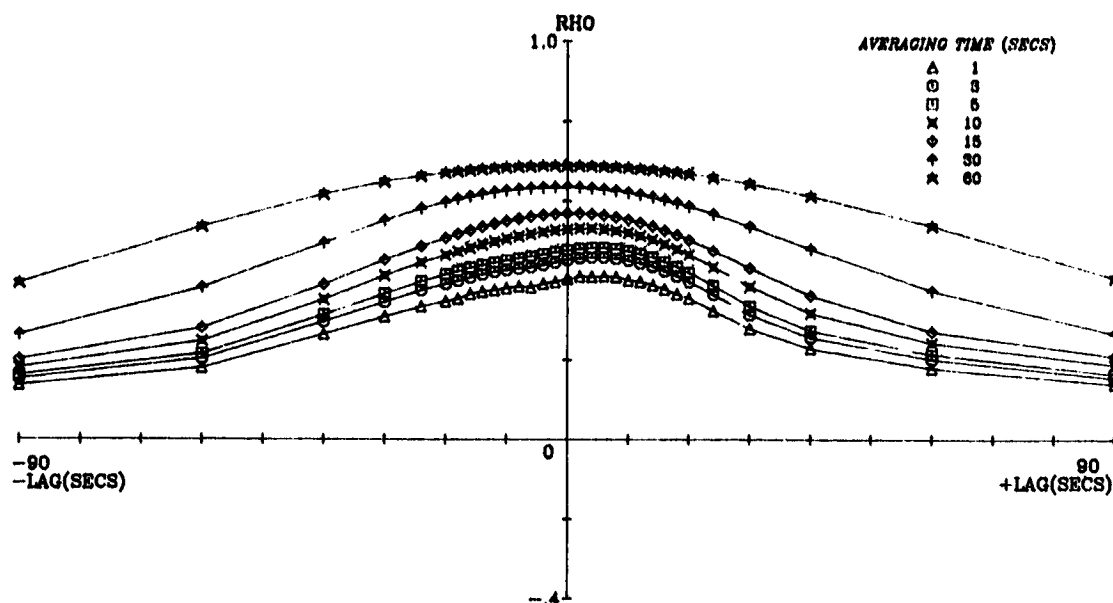


FIGURE 12. CROSS CORRELATIONS BETWEEN THE 30-m LEVEL ON THE METEOROLOGICAL TOWER AND THE POWER OUTPUT OF THE MOD-OA AT CLAYTON, NM FOR VARIOUS AVERAGING INTERVALS, AUGUST 22, 1980

The obvious conclusion is that the variance in turbine power output cannot be entirely explained by variances in short-term wind speed fluctuations from the type of anemometers used. Other parameters, such as wind direction, are also important. In addition, longer averaging times may also be appropriate.

The preliminary conclusion from all this in terms of site evaluation measurement strategies is that near-instantaneous samples once every few minutes are adequate for obtaining a site wind climatology, but some type of sample averaging is appropriate to better estimate turbine energy production. In addition, other parameters besides wind speed fluctuations are needed to better relate wind observations to turbine performance. These parameters are probably wind direction fluctuations and perhaps fluctuations in atmospheric density. Nonmeteorological factors, such as the interface between the turbine and the electric grid, may also come into play.

#### 4.0 SUMMARY AND CONCLUSIONS

Perhaps the best way to summarize this paper is by an examination of Figure 13. The goal is for a wind project developer to have as accurate of an understanding as possible of the performance of the turbine or turbine cluster on his proposed site. The "performance" includes energy production from the array as well as operation and maintenance costs. Determination of this performance depends to a large extent on

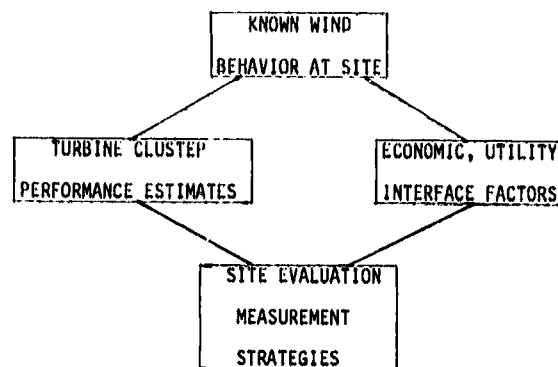


FIGURE 13. SUMMARY OF THE METEOROLOGICAL SITE EVALUATION PROCESS

an appropriate site evaluation measurement strategy. This paper has discussed how such a measurement strategy can be defined. First, a number of techniques are available to utilize existing data or short term (including intermittent) onsite measurements to obtain general knowledge of wind characteristics at the site. But in order to estimate cluster performance, actual onsite measurement programs must be established that reflects knowledge of turbine operating strategies, as well as factors relating to the interface between the turbines and the electric utility system. This nonmeteorological information can most likely be provided by manufacturers and utility personnel.

#### ACKNOWLEDGMENTS

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## QUESTIONS AND ANSWERS

R. B. Corotis and D. S. Renné

From: J. S. Anderson

Q: What physical process does Dr. Renné attribute to the rather long decay time of the autocorrelation function he showed?

A: *Decay times which give rise to 1 sec sample independence after about 2 min are associated with large turbulent eddies that move passed the anemometer. Decay times at other sites may differ from that found at Clayton, New Mexico.*

From: A. Jagtiani

Q: How many years should we collect wind data before we know if we have enough wind for a wind turbine installation?

A: *If it is known that the site will experience a large seasonal variation in the resource from the large scale climatology, a year's data is highly desirable. Whether one year's data is a reliable measure of the long term mean is dependent on the inter-annual variability at the site. Generally this can only be inferred from long term records at nearby locations. Judgments on the adequacy of the resource for turbine installation need to be tempered with the confidence needed of the estimate--a long period of record generally improves the confidence and accuracy.*

Q: How many anemometers should be used at a site to be sure of accurate wind speed readings?

A: *If the question refers to redundant data at a given height, the answer is one if reasonable quality control is exercised. If the question pertains to making extrapolations to hub height then a minimum of two anemometers is the answer. The use of three (or more) levels of anemometers, especially if all are located below the hub height will help improve the estimation of hub-height speeds. However, even in this case some extrapolation model (e.g., power law) is needed which will introduce uncertainty in the hub-height projected winds.*

Q: Where can I find tabulations of spatial standard deviations (etc.) for calculating the confidence interval associated with a particular station?

A: *Tabulations spatial standard deviations and cross correlations on scales pertaining to clusters of wind turbines are very scarce. Few data sets exist on which to make such calculations. Furthermore, it would be quite risky at this time to assume spatial correlations in one area are the same elsewhere. The work reported here will be published by Corotis as part of his report*

*to the Department of Energy. Spatial correlations on scales comparable to the separation of National Weather Service stations have been produced by Justus and others.*

From: J. W. Snow

Q: Does the term "numerical model" as used in your presentation mean a scheme which treats the physics of the atmosphere in some approximately complete way or does it mean a scheme based simply on the principal of mass conservation?

A: *The model applied in the study reported here was a mass consistent model. Parameterization of some physical properties, such as time variation of the height of the boundary layer, has been incorporated.*

From: G. G. Biro

Comment: The industry needs data on practical correlation between wind speed and machine performance. Specifically we need to determine the response time for wind turbines when wind reaches cut-in and cut-out speed as the wind speed is increasing or decreasing.

From: Anonymous

Q: You indicated that measuring the wind data sites 4 mo (once in spring, summer, fall, winter) for 3 yr would likely give a better estimate of the true annual mean than 1 yr for 12 mo. How about shorter periods--1 wk or 1 day?

A: *As you go to periods much shorter than 1 mo, i.e., a week or a day, the time scale of major weather systems becomes comparable to the averaging period and the inherent variability increases rapidly. Therefore, it is unlikely that weekly or daily averages, taken in each season for a period of 3 yr, would provide better estimates of the long-term mean than on average based on continuous measurements for a period of 1 yr.*

From: J. W. Snow

Comment: The atlases are biased in the direction of overestimating the wind resource because the interpolations assumed well-exposed sites, low roughness and no small-scale effects.

From: L. L. Wendell

Response: *The average wind power maps are not intended to represent estimates of the total magnitude of the wind resource. These maps are intended to indicate the wind power potential at a selected location provided it is well exposed to the wind. The areal distribution maps provide an indication of the degree of*

sheltering in an area due to general features of the surrounding terrain. Sheltering effects by small scale terrain features, vegetation of buildings would have to be determined by a site visit. This rationale is pointed out in the text of the atlases. There are certainly other approaches to presenting a wind resource analysis. The approach used by the Wind Characteristics Program was selected, after much deliberation and experimentation, to be most appropriate for the existing time and funding constraints.

## WIND TURBINE SITING: A SUMMARY OF THE STATE OF THE ART

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## ABSTRACT

The process of siting large wind turbines may be divided into two broad steps: site selection, and site evaluation. Site selection is the process of locating windy sites where wind energy development shows promise of economic viability. Site evaluation is the process of determining in detail for a given site the economic potential of the site. This paper emphasizes the state of the art in the first aspect of siting, site selection. Several techniques for assessing the wind resource have been explored or developed in the Federal Wind Energy Program. Local topography and meteorology will determine which of the techniques should be used in locating potential sites. None of the techniques can do the job alone, none are foolproof, and all require considerable knowledge and experience to apply correctly. Therefore, efficient siting requires a strategy which is founded on broad-based application of several techniques without relying solely on one narrow field of expertise.

## TECHNIQUES FOR RESOURCE EVALUATION

The main meteorological problem in siting is the variability of the wind resource. The variation in magnitude of the wind from one place to another makes site selection difficult. The variation of wind with time at a particular location complicates site evaluation. Wind characteristics such as average wind speed, turbulence intensity, and seasonal and diurnal variations can be significantly different over seemingly short distances. This means that there is only limited value in direct application of existing wind data collected at historical stations--stations that were probably established without wind energy applications in mind, such as airports or thermal power plants.

Since the wind resource variability is so great and the cost of onsite measurements can be large, there is great interest in techniques for

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estimating the wind energy potential of an area or site without having to initiate wind measurements everywhere. Numerous techniques for doing this exist or have been proposed. These techniques can be applied over large land areas to identify smaller high wind potential areas or they can be used to estimate wind behavior at a particular site. Among these techniques are:

- analysis of existing and supplementary wind data
- topographic indicators
- biological indicators
- geographical indicators
- social/cultural indicators
- numerical modeling
- physical modeling.

A brief description of these is given below. Further detail and references to original sources are found in [1]. Following these descriptions, example guidelines on their application in a siting program are given.

#### Existing and Supplementary Wind Data Analysis

Since the atmosphere obeys physical laws governing conservation of mass, momentum and energy, some knowledge of the state of the atmosphere at one or more points presumably should allow statements to be made about the state of the atmosphere at other points. The topographical indicator techniques and numerical and physical modeling techniques may be applied to make these statements. Basic input to each technique is some kind of analysis or summary of patterns of the meteorology at selected points throughout the territory being analyzed.

The elements to be characterized as a pattern depend upon the subsequent use of and references to these patterns. A reference to "prevailing northwest winds at the site" may be as close as one gets to recognizing a pattern at a very flat site. More formal recognition of patterns may be required if numerical models will be used. Whether or not air temperature is an element to be considered in the pattern recognition process is also dictated by the choice of analysis methods. For one type of numerical model discussed later, the fact that the valley winds can be cold does not matter. However, this might be a highly significant point to other kinds of models or to the meteorologist using topographical indicators.

When data from a single station are being analyzed, the common products used to characterize the wind behavior are frequency distributions of different wind behaviors of interest and averages. Innumerable displays of statistics could be used to characterize a measurement location. Table 1 provides some indication of the utility of several different single or joint frequency distributions.

TABLE 1. TYPICAL FREQUENCY DISTRIBUTION PRODUCTS  
AND THEIR POTENTIAL APPLICATIONS

<u>Dimensions of Frequency Distribution</u>	<u>Usefulness of Characterization of Wind Behavior or Analysis of Wind Potential</u>
Wind Speed	Estimating energy production.
Wind Direction	Assessing local or regional effects of topography
Wind Speed - Wind Direction	Determining principal directions of wind power. Necessary for cluster design.
Wind Speed - Time of Day	Determining diurnal load match. Caution is required, however, for vertical extrapolation of diurnal behavior.
Wind Speed - Month of Year	Determine seasonal load match.
Wind Direction - Time of Day - Month of Year	Assessing local or regional thermally driven wind systems, such as sea breeze or mountain-valley winds.
Duration of Wind Speed Persistence in Specified Speed Interval - Month of Year	Assessing probability of continuously available wind power. Determining partitioning of available wind energy between large-scale migrating storms and regional or local thermally driven wind systems. Determining optimum times for scheduled wind turbine maintenance.

More involved approaches are required to recognize wind behavior patterns using several meteorological stations instead of just one. The approaches range from highly subjective to completely automated objective derivation of categories of meteorological behavior.

One approach to use when analyzing data for a region is to establish a synoptic climatology. A synoptic climatology regards patterns of weather (winds, clouds, precipitation, etc.) as functions of the static surface pressure distribution [2]. Basic pressure pattern types are recognized using subjective or objective analysis of a long history of weather maps (which are contour plots of the atmospheric pressure field). Then, at every time in the record and for every location, a pattern type can be assigned. Following that, wind behavior at measurement sites is statistically analyzed as a function of pattern type, or wind behavior as a function of pattern type is estimated between stations by application of numerical models or topographical indicators for each type. With the statistics on the frequency of occurrence of each type determined from the assignment procedure, weighted average wind behaviors can be established at points of interest. Examples of this approach to preliminary resource assessments using subjectively derived pressure patterns or types are described in [3,4].

One objective procedure for pattern recognition is known as principal components analysis (PCA), also sometimes referred to as eigenvector or empirical orthogonal function analysis. PCA applications to wind energy problems have concentrated on patterns among wind vectors measured throughout a region prior to application of numerical models [5,6,1]. Consider wind speed and direction measurements made hourly at 10 locations for a year. The PCA technique (following the procedures of [5]) would mathematically determine 10 patterns, or eigenvectors. All 8760 hourly patterns could be described as variously weighted combinations of the 10 eigenvectors. A strength of the PCA analysis is that all 8760 hourly patterns could be approximately described using weighted combinations of just a few of the eigenvectors, with the remainder of the eigenvectors needed only to describe some small residual variance in the data set unexplained by the primary eigenvectors. It is frequently possible to assign some physical meaning to these primary eigenvector wind patterns, although this is not necessarily true since the eigenvectors are artifacts of an abstract mathematical procedure.

Once the eigenvectors and their weighting factors (known as the principal components) are determined, they may be used to generate approximate statistics of wind behavior at sites throughout the area. Days for which the behavior of the eigenvector weighting factors are similar can be identified. From each group of similar days, a typical day can be selected. Numerical models [5] or other techniques are then used to interpolate winds between measurement locations. Then, knowing roughly the frequency of occurrence of these typical days identified by PCA, one could generate statistics of wind behavior at any desired location. Alternatively, Endlich et al. [6] exploit the properties of a linear numerical model. That is, if the input data may be represented by 70% of eigenvector A, 25% of eigenvector B (and some residual variance), the solution can be represented by 70% of the solution for eigenvector A plus 25% of the solution for B. Since only a few eigenvectors can describe most of the input data set, the numerical model need be run only a few times. Weighted combinations of these solutions yield statistics (for as long a period as the data set) at any point in the region (Figure 1).

After analyzing wind patterns and applying other techniques to pick out likely high wind resource sites, one may wish to instrument those sites. Then there arises the problem of interpreting the climatological significance of the relatively short-term data. A basic first question to ask of a year's data at a candidate site is how representative of a long-term (e.g., 30 yr) mean is the measured annual mean, since annual energy production from a wind turbine will be roughly proportional to the annual mean wind speed. This question has been studied extensively [7,8,9] with roughly the same result based on analysis of numerous National Weather Service sites and across the United States and in Hawaii and Alaska. As a national average, there are regional variations [7] the climatic mean wind speed will be within  $\pm 10\%$  of a single annual mean wind speed observation 90% of the time.

Attempts to adjust the climatic wind speed estimate using a season or year of site measurements and a comparison with nearby climatic data

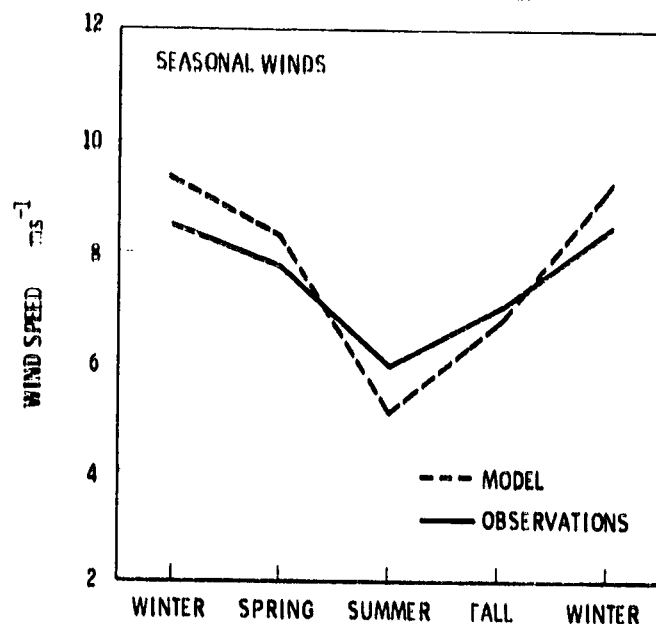


FIGURE 1. COMPARISON OF OBSERVED AND PREDICTED SEASONAL MEAN WIND SPEEDS FOR MT. TOM, MASSACHUSETTS. PREDICTIONS BASED ON AN EIGENVECTOR ANALYSIS PROCEDURE BASED ON A MASS CONSISTENT MODEL [6].

have been made [1,7,8,10]. The simplest approach is to determine the ratio of the mean wind speeds simultaneously measured at the site and the climatic station and multiply the ratio by the climatic wind speed measured at the climatic station. This essentially assumes that monthly or seasonal mean wind speeds are perfectly and linearly correlated (a correlation coefficient of  $r = 1.0$ ) (a) at all locations with an area. Typical correlation of monthly mean speeds between sites within 100 km of each other in fairly simple terrain is  $r \approx 0.4-0.5$ ; for annual means  $r \approx 0.3-0.5$  [7]. Corotis [8] suggests an adjustment that incorporates the correlation explicitly. However, ample evidence exists to show that adjustment of annual or monthly mean wind speeds does not yield significant and reliable improvement in estimates of the climatic means [1,7,8]. Furthermore the correlation of annual and monthly means between sites is a very sensitive quantity, because the interannual standard deviations are small [1,8].

#### Topographical Indicators

Historically, wind machines have been sited by applying topographical indicators, which are empirical guidelines describing the general

- (a) The square of the correlation coefficient,  $r^2$ , is a measure of the fraction of the variance about the mean value that is attributable to the relationship of two quantities. Thus, if the correlation between monthly means at two sites is  $r = 0.5$ , only 25% of the variance about the climatic mean at each site may be attributed to a correlation between monthly means at the two sites.

effects of terrain or surface obstacles on the wind. Recently, topographical indicators were used extensively in the DOE regional resource assessments. Topographical guidelines are based on a physical understanding of how topography affects flow and on experience gained through observation. An understanding of these guidelines is also invaluable in interpreting the results of numerical and physical modeling studies and measurements.

A number of topographical features are recognized as indicators of high wind energy potential. One group includes gaps, passes, and gorges in areas of frequent strong pressure gradients. These strong pressure gradients occur when large temperature gradients form across a mountain barrier. For example, coastal mountains separate a nearly uniform temperature marine air mass from continental air masses. The inland air can become hot in summer or daytime, or cold in winter or at night, thereby causing seasonal and diurnal fluctuations in the pressure gradient across passes. Pressure gradients also form across mountain ranges when strong winds, as from a storm, blow up against the mountain barrier. If the flow has insufficient kinetic energy to cross the potential energy barrier that the mountains represent, the gaps, passes, and gorges are the relief points for the winds driven by the storm.

Long valleys extending parallel to prevailing wind directions are often good wind energy regions also. The wind stream is channelled by the valley walls. At narrow points along a broad valley, mass conservation causes winds to accelerate through the constriction. In the opposite way the river of air spreads out and slows down where the valley widens.

Summits of ridges and mountains usually provide enhanced wind resource areas. Over small-scale hills and ridges (less than 300 m high), the air accelerates over the crest. This is also due to mass conservation; a stream of air is vertically compressed as it flows over the hill and so must move faster in the constricted region. This is not necessarily so for the flow over large-scale mountains. The winds at summit elevation of a high mountain may actually slow down near the summit because of the drag that the mountain exerts on the flow. However, mountains and ridges are still usually good resource areas because they are like tall towers that intercept the flow at higher levels where winds are usually stronger.

Some features that indicate low wind energy potential are basins and valleys that are perpendicular to the prevailing wind. These features can be low wind areas because the flow spreads out over them, opposite to the effect of flow acceleration over ridges, or because they collect cold, heavy air that stagnates at potential energy minima.

Proper use of topographical indicators requires an experienced boundary layer meteorologist because the issue of when and how to use them, and how far to trust them, are complex. Consider the complexity of flow over a small isolated hill. Wind speeds at a given height above the terrain surface usually are higher over the summit of a hill than over surrounding lowlands. One experiment reported by Bradley [11], designed to collect a data set for testing of numerical and analytical

models of flow over hills, consisted of detailed measurements from a tower atop a 170-m hill and from another tower on the flat plain upwind of the hill. Reasonably good comparisons between model predictions (based on the upwind tower measurements) and the summit measurements were obtained for a very restricted set of atmospheric conditions. The first restriction was that the atmospheric stability was nearly neutral, which means that the vertical temperature structure is such that buoyancy forces on warm or cool parcels of air do not contribute to generation (unstable conditions) or suppression (stable conditions) of turbulence, and hence do not contribute to mixing of mean wind speeds from different levels. The second restriction was that the height of the planetary boundary layer (PBL) was at least 500 m above the plain. The top of the PBL is often made visible by the temperature inversion that forms a "lid" that traps smog beneath it. Oftentimes the wind speed increases as air flows through the constriction formed by the temperature inversion and the hill, but due to the complicated response of the atmosphere this may not always be so. Bradley states, "Several occurrences of the distortion of [wind] profiles by the low-level inversion have been observed but were not consistent, sometimes resulting in strongly accelerated flow at the upper levels on the tower, and at other times strong retardation."

The example illustrates that even in the most simple of cases, topographical indicators provide only qualitative information. Generic flow guidelines have been developed from theory, from numerical and physical simulations of flow over model terrain, and from actual measurements of flow around full-scale features. Succinct generalizations drawn from these studies are useful; however, reliance upon them must be tempered. Topographical indicators should therefore be used as guidelines to:

- understand flow-terrain interactions
- indicate where to look for, or when to use, other indicators
- indicate where to make measurements
- interpret measurements already made.

#### Biological Indicators

The study of tree deformation indicates that trees are a useful tool for determining prevailing wind direction, identifying areas where severe wind and/or ice loads may occur, and for estimating mean annual wind speed. Estimates of mean annual wind speed based on wind-deformed trees, although subject to some uncertainty, are simple, quick, inexpensive and usable for identifying locations where more detailed wind measurements are justified, and as a guide for preliminary ranking of sites in terms of wind power potential.

The degree of permanent tree deformation has been calibrated against the annual mean wind speed for numerous genera of trees [12]. This was accomplished by measurement of the annual mean wind speed near several trees of each genus and determining a linear relationship between the value of various indices of tree deformation and the measured mean wind speed. Several indices of tree deformation were explored. The Griggs-

Putnam index for conifers and the Barseh index for deciduous trees subjectively categorize the degree of deformation into eight classes. The deformation ratio measures various angles of tree crown asymmetry and trunk deflection. The compression ratio measures asymmetry in the tree ring growth in the trunk.

The Griggs-Putnam Index or the Barseh Index, in general, provide the best estimates of mean annual wind speed. The mean wind speeds and the 95% confidence limits as a function of index value were determined for many genera of trees [12] and also reported in [1]. However, it is best to interpret tree deformation in a local region as a relative indicator of wind speed. The data used in [12] represent trees and wind measurements that span much of the U.S., but calibrations can vary locally [13]. In addition [13] found that deformation of California Oaks could not adequately discriminate between the intermediate wind speed indices, and suggested this may be due to the effects of local winter ice loading on the trees.

In mountainous areas, winds are complex and the sparse wind data available provide little information on wind direction. By observing flagged trees, the branches of which grow away from the prevailing wind direction, the direction of flagging can be determined and marked on a topographic map. In this way, the mean flow pattern in a local area can be noted.

Trees can also be used as indicators of destructive forces of severe wind and icing, which may present problems for wind turbines, their support structures, and the power transmission lines from the turbines [4,12]. Broken branches, wind throw (leaning trees) and blow-down are all evidence of severe winds. Trees with broken branches or tops and a lack of bark on the upwind side can indicate severe winds or wind-driven ice.

#### Geomorphological Indicators

When winds interact with and alter the earth's surface, the geomorphological features that result are called eolian landforms. Especially in arid regions where vegetation is sparse, winds can erode the surface, transport sand and dust, and deposit sediment. The erosional and depositional eolian landforms and the characteristics of the transported sediments are indicators of the history of the winds that caused these landforms.

Geomorphological interpretative techniques can be applied for three purposes:

- to indicate that a relatively good wind resource exists where eolian landforms are present
- to determine crude estimates of mean wind speeds from observed sand dune migration rates, sand size particle distributions, and sand ripple formation [1,14]
- to indicate prevailing wind directions.

The principal difficulty with estimating wind speeds using these techniques is that substantial prior knowledge of the wind climatology is required. For example, how much of the total dune migration is cancelled by winds of opposite directions, or how frequently are winds strong enough to cause the sands of a certain size to move? If those answers are in hand prior to eolian feature analysis, why carry out the analysis?

Information gained from the use of geomorphological indicators is sometimes helpful in forming an integrated picture of the wind regime in a data-sparse area. However, the effort expended should be compared with the great uncertainty of the technique. Aerial photographs may be obtained during the early stages of the siting process for purposes other than for examining eolian landforms. If eolian indicators are found in the photographs, interpret the photographs as quickly as possible and use geomorphological indicator techniques only as part of site visits that include other activities, e.g., setting out anemometers or inspecting terrain feasibility. In this way, information can be added to the data base of the site without undue delay and expense.

#### Social and Cultural Indicators

Human cultural and behavioral responses to the climatic wind resource provide indications of the wind resource characteristics, just as geomorphology and ecology are partially determined by the wind. A sharp observer exploring a candidate resource area should actively look for and evaluate clues provided by social and cultural indicators of wind. Some examples are:

- location of grazing land versus crop land
- evidence of past use of wind power
- roadway signs
- evidence of past use of wind power
- roadway signs
- wind damage to power lines, buildings, billboards, etc.
- location of snow fences.

Long-time residents of an area, especially those that work outdoors and cover a large territory (such as utility linemen), can sometimes provide useful information. However, people tend to overestimate average wind speeds because they remember specific discrete wind events rather than average conditions. Even so, a person may be able to say with considerable confidence that region X has more wind than region Y. If region Y is near an existing anemometer, then some useful information may be available to incorporate into the evaluation.

#### Numerical Modeling

A numerical model consists of a set of equations that are assumed to adequately represent the process being studied and a procedure for solving these equations. Unfortunately there is no general solution to the equations that describe those processes. A common approach is to



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enlist the assistance of computers to numerically achieve a solution to the fundamental equations, also known as primitive equations. Even numerically derived solutions of the primitive equations are extremely difficult and costly to obtain, so other approaches seek to simplify the problem by starting with a set of simpler equations, e.g., a set that only considers conservation of mass.

The advantage of numerical modeling as a tool for siting is that numerical models provide an objective method for estimating the effects of terrain on airflow and for interpolating wind data from locations where there are observations to locations where there are none. The primary disadvantage associated with the use of numerical models is the uncertainty in their accuracy, which is due to lack of verification. There have not been enough experiments in which model simulations have been compared with good field measurements. This will remain the case for a long time, since there are not very many good data sets for experiments of this type. The expense of gathering good verification data is large. The only alternative is good judgment. The person analyzing model results should accept or reject them on the basis of how well he feels the model simulates the important physical processes controlling the flow.

A primitive equation model available at the University of Virginia was tested with wind turbine siting applications in mind [15]. Figure 2 compares model predictions of wind power density (units of  $100 \text{ W/m}^2$ ) with measurements obtained primarily from a research aircraft that flew a rectangular pattern over the Delmarva Peninsula. The general pattern of the wind power field (inland minimum, coastal gradient, offshore maximum) is reproduced by the model, but the model missed on details of the magnitudes.

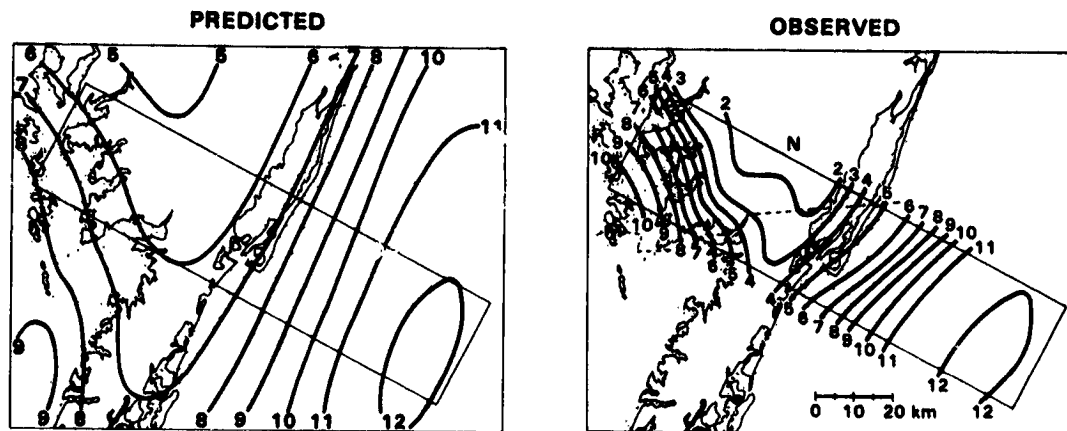


FIGURE 2. AREAL DISTRIBUTION OF PREDICTED AND OBSERVED WIND POWER DENSITY ( $100 \text{ W/m}^2$ ) AT 170 m ABOVE THE SURFACE OVER THE DELMARVA PENINSULA. PREDICTIONS MADE BY THE UNIVERSITY OF VIRGINIA MESOSCALE MODEL INITIALIZED FOR 30 JAN 80, 0828 EST.

In an analysis of the skill of the model [15], it was argued that prediction errors must be partitioned into those due to inadequacies of the model and inadequacies of the initial data used to start and carry out a simulation. It was argued that the skill of choosing initial data was lower than the skill of the model. In the same study, the model predictions showed no skill at all in the South Texas Coast area. That was attributed to the diurnal variations of the large-scale pressure field caused by the gently sloping topography in the south central United States. Those variations were not incorporated into the initial and boundary conditions. That study concludes: "We conclude that for coastlines with little topography, the mesoscale model usefully predicts the magnitude and location of the centers of maximum and minimum wind power. For coastal areas with considerable topography, a more complete initialization of the model is required." In fact, whether or not primitive equation models can operate successfully for wind energy assessments in areas of significant topography is still a matter that is under research scrutiny.

A simpler class of models that attempts to satisfy many of the physical laws of a complex primitive equation model but at a small fraction of the cost is conceivable. Most of these would be generally referred to as two-dimensional models. One type of two-dimensional model simulates air flow in a vertical plane by specifying that terms in the equations dealing with variations perpendicular to the simulated plane are non-existent. For example, flow from the ocean over a coastal ridge might be simulated with such a model. Often times this type of two-dimensional model is developed as a subset of a larger three-dimensional primitive equation model and used for initial tests prior to a full-scale three-dimensional model run. Other two-dimensional models solve equations describing flow in some suitably defined layer near the ground, usually the planetary boundary layer, which may be several hundred meters to a few kilometers thick. Layer-averaged primitive equation models [16,17] require surface and lateral boundary conditions similar to more elaborate models, but a number of questionable assumptions must be made about conditions at the top of the layer. The same is true for layer-averaged models that solve simplified equations derived from the primitive equations [18]. How the upper boundary is modeled will have a significant impact on the resulting near-surface windfield for reasons related to processes discussed previously under topographical indicators. Although these models should be able to mimic certain effects where differences in surface temperature, surface roughness, and elevation are present, there has not been much verification effort. Consequently their reliability and accuracy related to wind energy applications is still poorly known.

The simplest models that have been used for wind energy applications are known as objective analysis or mass-consistent models [1,5,6,19,20]. These models use input data and some initialization scheme to generate a wind vector at each point in a three-dimensional grid. This initial windfield is then adjusted with successive iterations until the windfield satisfies the physical constraint imposed on the solution, namely, the conservation of mass. Mathematically, the minimum adjustment possible is made so the flow is as near the initial guess as mass consistency allows. The quality of the initial guess windfield is

obviously critical. Other conditions in the model determine how the adjustments are achieved. The lower boundary condition requires the surface winds to be parallel to the terrain slope. A model parameter controls how much adjustment takes place in the vertical dimension rather than horizontally, thereby controlling how much air blows over a ridge and how much goes around. The height of the top of the modeled region can be varied (tuned) to control the amount of speedup realized over mountain summits [6].

Objective analysis models have received the most attention for verification studies for wind energy applications [1]. The general results are usually quite reasonable. A modeling study of Oahu [21], for example, showed some reduction of wind speed upwind of the steep windward ridge, maximum winds along the ridgetops, and light winds in the lee of the mountains. Of course, those general predictions are just what one would expect from application of topographical indicators.

Table 2 provides a perspective on numerical model accuracy and relates it to accuracy achievable through use of topographical indicators. The table shows, for example, an Oahu simulation using a high data density input [21]; that of the four windiest sites predicted with the model, only one was actually observed to be in the four windiest sites. However, five of the top seven (and nine of the top ten) sites predicted were actually observed in the top seven (and top ten) most windy sites. The table indicates that there is a 20% chance that the result could have been obtained through a random selection of any four of the sites. However, there is just a very small chance that random selection of seven of the 20 sites would result in at least five of the observed top seven sites being selected. These results suggest that the model should be used as an indicator of high wind resource areas from which several sites may be selected for further consideration or instrumentation, but that the model should not be relied on to pinpoint the absolute best site.

The results in Table 2 from modeling the Nevada Test Site [22] differ somewhat from the Oahu results. Three of the top four sites were selected by the model but only five of the top ten. This occurred because the best sites were on well-exposed high ground, easily discriminated by the model, whereas the remainder of the sites did not span a very large range of mean wind speeds.

Table 2 also shows results from a ranking of the 20 Oahu and the 20 Nevada sites where a meteorologist experienced in the use of topographical indicators and unfamiliar with the model verification studies, determined a rank. Evidently, a qualified meteorologist can compete fairly well with the mass consistent models.

A model's accuracy should also be judged in terms of the use of its output. A first investigator might claim the seasonal trends shown in Figure 1 are well captured by the model. A second might say that the error of nearly 1 m/s in the mean in every season but Fall represents a significant error in the prediction of site energy production. And a third might counter the second by questioning the accuracy with which energy production estimates can be made and by pointing out that the

TABLE 2. NUMBER OF SITES OBSERVED IN TOP X SITES  
THAT WERE PREDICTED TO BE IN TOP X SITES

The value in parentheses is the chance that the tabulated  
result could be achieved by random selection

Case and Prediction Method	Top X Sites of 20		
	X=4	X=7	X=10
Oahu, NOABL <sup>(a)</sup> , 6 stations plus rawinsonde input [21]	1 (20%)	5 (<1%)	9 (<1%)
Oahu, NOABL, rawinsonde input [21]	1 (20%)	5 (<1%)	8 (<1%)
Nevada, NOABL, 6 stations plus rawinsonde input [22]	3 (<1%)	4 (1%)	5 (2%)
Oahu, topographical indicators <sup>(b)</sup>	3 (<1%)	6 (<1%)	8 (<1%)
Nevada, topographical indicators <sup>(b)</sup>	2 (3%)	3 (3%)	6 (1%)

(a) NOABL is the name of a mass consistent objective analysis  
model [20]

(b) The rank was determined independently using topographical  
indicators by a recognized expert.

importance of the errors may vary seasonally as the fuel mix of the  
utility varies seasonally.

### Physical Modeling

Physical modeling involves placing a scaled model of an object into a  
wind tunnel, water tunnel (also known as a flume), or a towing tank in  
order to determine how the object interacts with a fluid flowing over  
it. If the modeling study is constrained to consider only those prob-  
lems that can be properly posed in a flow facility, physical modeling  
can yield results more accurate than numerical models. Physical  
modeling of atmospheric flows does require large, specialized facili-  
ties, however.

The theoretical foundation of physical modeling is the principle of  
similarity. The principal states that if certain constraints are met,  
flow over a dimensionally similar model will be identical to flow over  
the full-size object--as long as boundary conditions are also the same.  
The constraints can be found by analyzing the equations that describe  
fluid flow.

The equations describing air flow in a wind tunnel are identical to the  
equations describing flow over full-scale terrain (and the same as the  
primitive equations discussed under numerical modeling). What differs  
between wind tunnel and full-scale flows is the relative importance of

various terms in the equations of motion. The importance of various terms in the equations of motion is related to the relative values among a group of dimensionless numbers. The Reynolds number,  $Re$ , describes the ratio of accelerations in the flow to viscous forces (actually, force per unit mass, hence units of acceleration). At high Reynolds numbers typical of atmospheric flows, the value of  $Re$  characterizes certain properties of the turbulence structure of the flow. The Rossby number,  $Ro$ , relates the accelerations in the flow to the effects (Coriolis force) due to the earth's rotation. The Rossby number is small, meaning rotation is an important aspect of the flow, if large (1000 km) sections of terrain are being studied. The ratio of accelerations to buoyancy forces is expressed in the Froude number,  $Fr$ . Atmospheric stability, which depends on the vertical variation of wind and temperature, is reflected in the Froude number. Atmospheric stability controls detailed characteristics of the turbulence structure, which in turn feeds back to affect the wind structure, so the Froude number is an important descriptor of the flow.

Analysis of the equations of motion shows that the key requirements for modeling atmospheric flow for wind energy purposes are a region smaller than a few tens of kilometers, a large Reynolds number, a Froude number identical to the actual flow, and identical initial and boundary conditions [1]. Strict similarity is impossible to achieve for all flows. For example, maintaining Reynolds number similarity within full-scale and laboratory flows may make it impossible to maintain Froude number similarity. How satisfactorily a physical model satisfies these requirements is largely a function of stability. The similarity constraints are met most easily for slightly to moderately unstable flows when local terrain relief is small compared to the depth of the boundary layer. Under these conditions, flow in the boundary layer should be fairly homogeneous and the wind profiles simple with little turning of the wind vector with height. This situation results in fairly simple boundary conditions and the atmospheric flow can probably be represented by a neutral stability boundary layer in a wind or water tunnel.

#### APPLICATION OF THE SITING TECHNIQUES

The siting techniques discussed above are applied differently, or not at all, at various points in the siting process depending on the particular problem at hand. Currently, a siting methodology is under development<sup>(a)</sup> that encompasses all siting issues, not just the meteorological aspects of siting. Four stages of siting are identified:

- I Identification and Ranking of Candidate Resource Areas
- II Selecting Potential Candidate Sites
- III Selecting Candidate Sites
- IV Selecting Preferred Sites.

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(a) Electric Power Research Institute project RP-1520, Developing a Wind Turbine Siting Methodology for the Utility Industry.

The following is a description of how a meteorologist might undertake the second stage, which is most like what one might call wind prospecting. Further guidance for this and other stages may be found in [1] and the forthcoming EPRI report.

Stage II seeks to identify Potential Candidate Sites (PCS) within the identified Candidate Resource Areas (CRA). The usable siting techniques in an approximate order of cost effectiveness are:

- evaluated existing data
- topographical indicators
- biological indicators
- social and cultural indicators
- numerical modeling
- geomorphological indicators.

The meteorologist should begin by determining the meteorological patterns that dominate winds in the CRA. Especially important are the wind directions. Then, topographical maps would be consulted. When the wind patterns are interpreted with the topographical indicators, the meteorologist should be able to identify the best likely wind zones. Looking more closely at the topography within each zone, the meteorologist could even begin to make a tentative list of locations from which the list of Potential Candidate Sites may later emerge.

The most cost-effective thing to do at that time is to have the meteorologist go to the CRA, drive through it and examine it for biological, social/cultural, or geomorphological indicators. Special, though not exclusive, attention should be paid to the sites on the tentative list of locations developed prior to going out in the field. During this drive through the CRA, the meteorologist will clearly be somewhat confined to stay near roads (road qualities and bridge load limits should be considered for possible future construction access) and possibly transmission lines. On this drive through the CRA, the meteorologist may formulate a recommendation on the necessity of performing off-road prospecting trips, aerial surveys, or application of numerical modeling studies.

If the topography is hilly or mountainous and the meteorologist sees no consistent evidence from biological or geomorphological indicators, the use of numerical models should be considered. Physical modeling is not appropriate because of the large terrain areas involved. The mass-consistent models are probably the easiest to apply. However, since mass-consistent models tend to predict just what one would predict through application of topographical indicators, the time and expense of a field program just to obtain data to drive a model must be carefully weighed against the anticipated results. It is probably more prudent to first run the model with available data. The sensitivity of the model predictions to variations or adjustments to the input data should be determined. If little sensitivity is found, one could accept the indications of the high wind areas and go examine those areas for supporting evidence (such as deformed vegetation). If a great deal of sensitivity is found, supporting field measurements should be considered. But the reason for the sensitivity should also be considered.

The model may not be handling the specific simulation well, in which case its predictions will be suspect. Or, the sensitivity may be due to real physical interaction between winds and terrain. In that case, the sensitivity should raise the question of whether or not there might be troublesome high variability of the wind resource in that area.

The primitive equation models theoretically should perform better in the flatter coastal candidate resource areas where surface temperature and roughness variations are significant. Recall, however, from the discussion on numerical modeling above, that a sophisticated primitive equation model failed to demonstrate skill in its predictions on the south Texas coast due to the fact that subtle diurnal changes in the large-scale atmospheric pressure field were not incorporated into the input conditions. That kind of failure to obtain proper input could easily occur in the actual application of models by utility subcontractors. The evidence of failure wouldn't appear until after verifying site measurements were made. Again, the best use of the models is probably in sensitivity testing.

#### SUMMARY

There are wind resource evaluation problems to solve at all stages of the siting process. The problems stem primarily from the spatial variability of the wind resource, which makes site selection difficult, and from the temporal variability of the resource, which makes the estimation of long-term wind statistics difficult. Numerous techniques for solving these problems have been studied, and are summarized in this paper.

The current capabilities and limitations of each technique are fairly well-known. As a result, some techniques are applicable only to certain problems. Efficient solution of the meteorological siting problems at each stage of the siting process requires a strategy for applying the techniques. The strategy should be governed by applying techniques together or in sequence at each stage. This is done in a way that the first techniques(s) applied produce the most information toward satisfying the objectives of each stage for a given increment of cost. A suggested guideline for one stage is given. The actual strategy used for any specific siting problem will require fine tuning by the boundary layer meteorologist overseeing the wind resource evaluation efforts.

#### ACKNOWLEDGMENTS

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LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Rotor Blade Design and Fabrication

Session Chairman - T. L. Sullivan (NASA LeRC)

"Fiberglass Composite Blades for the 2 MW Mod-1 Wind Turbine Generator"  
W. R. Batemore  
(Kaman Aerospace Corporation)

"Low-Cost Composite Blades for the Mod-0A Wind Turbine"  
O. Weingart  
(Structural Composites Industries, Inc.)

"Fiberglass Composite Blades for the 4 MW - WTS-4 Wind Turbine"  
R. J. Buonolari  
(Hamilton Standard Division of United Technologies)

"Design and Evaluation of Low Cost Blades for Large Wind Driven Generating Systems"  
W. S. Eggert  
(The Budd Company Technical Center)

"The Development and Manufacture of Wood Composite Wind Turbine Rotors"  
M. D. Zuteck  
(Gougeon Brothers, Inc.)

"Structural Fatigue Test Results for Large Wind Turbine Blade Sections"  
J. R. Faddoul  
T. L. Sullivan  
(NASA LeRC)

FIBERGLASS COMPOSITE BLADES FOR THE 2 MW  
MOD-1 WIND TURBINE GENERATOR

W. R. Batesole  
Kaman Aerospace Corporation  
Bloomfield, Connecticut

ABSTRACT

In mid-1979, NASA contracted with Kaman Aerospace Corporation for the design, manufacture, and ground testing of two 100 foot composite rotor blades intended for operation on the Mod-1 wind turbine. NASA stipulated that the blades utilize, to the maximum extent practicable, the technology developed in a forerunner program in which Kaman produced a 150 foot test blade.

The Mod-1 blades have been completed and are currently stored at the Kaman facility.

This paper describes the design, tooling, fabrication, and testing phases which have been carried out to date, as well as testing still planned. Discussed are differences from the 150 foot blade which were introduced for cost and manufacturing improvement purposes. Also included is a description of the lightning protection system installed in the blades, and its development program.

Actual costs and manhours expended for Blade No. 2 are provided as a base, along with a projection of costs for the blade in production. Finally, cost drivers are identified relative to future designs.

INTRODUCTION

Thus far, large U. S. wind turbine generators have utilized rotor blades made from metal or wood, since the technology involved in these materials is well understood. However, the use of composite construction has long been considered to also have excellent potential for large blades. The advantages of glass fiber reinforced composite structure include:

- Nearly unlimited design flexibility in adopting optimum planform tapers, wall thickness taper, twist, and natural frequency control
- High resistance to corrosion and other environmental effects
- Low notch sensitivity with slow failure propagation rate
- Low TV interference
- Low cost potential due to adaptability to highly automated production methods.

Composite construction has been in successful use for some years in helicopter rotor blades. To assess the state of composite technology for wind turbine blades, especially in the very large sizes, NASA contracted with Kaman Aerospace Corporation in 1977 to design, build and ground-test a 150 foot all-composite blade. This program (see Reference) was accomplished successfully; i.e., design and manufacturing methods were developed, the blade constructed, and measurements and structural testing confirmed that the design analysis methods had satisfactorily predicted the strength and dynamic characteristics of the final article. The 150 foot blade is the largest composite rotor blade ever constructed.

Based on the encouraging results with the 150 foot blade, NASA decided to extend the investigation of composite blades into an operational test phase. Accordingly, NASA contracted with Kaman, in mid-1979, to design and build two 100 foot blades to be installed and evaluated on the Mod-1 wind turbine in Boone, N. C. NASA stipulated that these blades were to directly utilize the technology developed in the 150 foot blade program; i.e., they were to be designed and manufactured using the same methods and basic structural configuration. In this program, NASA assumed responsibility for assuring compatibility of the blades with the Mod-1 system; to this end, NASA provided all design load cases and interface parameters. Kaman's task was to carry out the structural design and analysis, manufacture the tooling and the blades, and conduct limited ground testing prior to delivery.

#### SUMMARY

At this writing, the design and construction phases of the Mod-1 composite blade have been successfully accomplished. The two blades are completed, as shown in Figure 1, and are stored at the Kaman facility pending availability of funds for completion of the ground-test phase of the contract, followed by shipment and installation on Mod-1. The 150 foot blade, which preceded the Mod-1 blades, is shown in Figure 2.

Two primary constraints were influential in the design; first, the blades were to directly utilize the 150 foot blade technology, and second, the composite blades were required to match the static and dynamic characteristics of the steel blades they are to replace. The latter requirement proved to be particularly challenging since the modulus of elasticity of the composite is approximately one-sixth that of steel. Considerable care was thus required in selecting cross sections and wall thicknesses of the spar, which is the blade's main structural element. Achieving appropriate stiffness and dynamic properties was greatly facilitated by the nature of composite construction which readily permitted dimensional variation to be built into the spar as required.

The Mod-1 blades utilize wound fiberglass Transverse Filament Tape (TFT) for the spar, a material used in the commercial pipe industry and further developed for the 150 foot blade. The afterbody portion of the airfoil is comprised of upper and lower panels of fiberglass and paper honeycomb sandwich construction. Means of attachment to the wind

turbine hub is provided by a steel adapter fitting, permanently mounted in the blade spar at the inboard end. Use of an aft spar member at the trailing edge, such as that employed in the 150 foot blade, is eliminated in the Mod-1 design for simplification and cost saving. A lightning protection system is incorporated in the Mod-1 blades. The system was developed under the contract, using the services of a lightning test laboratory for developmental testing and substantiation of the design. This was a new development, not having been provided in the 150 foot blade. The resulting protective system has been shown capable of sustaining the 200,000 ampere stroke level specified by NASA.

The blades were weighed and CGs measured. Final blade weight is 26,846 lbs which represents an increase over the steel blade weight; however, since the spanwise CG location is farther inboard than that of the steel blade, the growth in mass moment is minimal and satisfactory for Mod-1 use.

Certain planned testing of the finished blades, and installation of the required instrumentation, is being held in abeyance pending DOE funding for continuation of the Mod-1 wind turbine program.

Cost of manufacturing the Mod-1 blades was carefully tracked. Blade No. 2, which is considered the more representative base case, cost \$307,000. This projects to approximately \$5.70/lb for the 100th blade with appropriate tooling and the application of a learning curve. The requirements to utilize the 150 foot technology and to match the steel blade's properties, represent some compromise to production design and, hence, to cost. Elimination of this effect could reduce the above cost per pound figures by 25 to 30%.

## DESIGN

### Design Concept

NASA retained responsibility for the interface of the blade to the wind turbine. To assure compatibility, NASA provided all design parameters, as well as the static and fatigue load cases required by Kaman to carry out the structural design.

Also stipulated was the basic configuration of the blade, which was required to utilize the design features of the 150 foot blade to the maximum extent. However, as the design process evolved, Kaman recommended certain changes to the configuration to introduce more recent thinking in blade construction and to effect a reduction of complexity and cost. One such change, concurred in by NASA, was elimination of the trailing edge as a primary structural member reacting edgewise bending. This allowed deletion of a trailing edge spline, as well as the inboard truss structure necessary to accommodate spline loads in the 150 foot blade. In the Mod-1 blade, the forward spar was increased in its chordwise dimension to serve as the main structural member, carrying the primary loads. Afterbody panels react only local airloads.

The requirement that the Mod-1 blades duplicate stiffness and natural frequency characteristics of the Mod-1 steel blades, resulted in growth of the blade inboard beam thickness to effect the necessary sizeable increase in section moment of inertia. Chord length was required to grow in proportion; thus, the blade's planform and root thickness represent the most evident difference from the Mod-1 steel blade. This entailed some compromise in performance, weight, and cost from an optimized blade design.

### Configuration

The Mod-1 blade is shown in Figures 3 and 4 which depict the planform and cross section.

### Critical Structural Areas

#### Spar Buckling

Discussed earlier was the required stiffness match of the composite blade and steel blade. Since stiffness is a function of the product  $EI$ , and the  $E$  value for the glass fiber/epoxy composite is approximately one-sixth that of steel ( $5 \times 10^6$  psi vs  $29 \times 10^6$  psi), it was necessary to provide a compensating increase in  $I$  by means of larger cross sections. However, with blade weight also a prime consideration, the wall thickness of the larger size shell had to be held to a minimum; thus the critical design consideration became buckling or wall crippling in a thin-wall shell. Fortunately, Kaman's analytical programs for design of TFT composite shells had been substantiated by empirical results of the full-scale buckling test in the 150 foot program. In addition, a trial Mod-1 spar was manufactured and subjected to further buckling tests to provide direct correlation of analysis and actual results. Thus, the final spar is considered well designed and substantiated for strength under the critical buckling load cases; these proved to be the emergency rotor overspeed and the hurricane wind condition.

In addition to providing adequate buckling capacity, the spar also was designed to meet the bending moment distribution called for in NASA's design specification.

#### T-Clip

The afterbody panels attach to the spar by means of a lap joint and a T-clip for the outer and inner panel skins, respectively; this is shown in Figure 4. The cavity between these attachments is filled with syntactic foam to act as a shear connection, reacting the shear loads resulting from applied airloads over the panel area.

The T-clip reacts tension loads in the panel inner skin arising from the panel reacting airloads as one member of a truss in conjunction with the lower panel, and due to bending in the panel itself. The T-clip is a structural connection whose principal design challenge lies in developing an arrangement which can be manufactured with consistent bond quality in a relatively inaccessible area. The solution proved to

be a good example of a cooperative effort among engineering personnel in the design, stress, materials, and manufacturing disciplines, acting together to develop a satisfactory design. The result is considered a significant improvement in strength and consistency over the T-clip of the 150 foot blade. Development of the manufacturing technique was carried out on a full-scale section of the outboard 30 feet of the blade.

#### Adapter/Spar Attachment

As in the 150 foot blade, a steel adapter fitting is located at the in-board end, attached to the composite spar by means of a double row of bolts (18 total) as shown in Figure 5. A large diameter bushing is employed at each bolt, seated by means of a heavy clamp load against a spotfaced surface of the adapter fitting. Thus, the bushing serves essentially as a rigid stud, integral with the adapter fitting. Deflection of the joint under the eccentric loading, inherent in the single-shear arrangement, is accommodated by means of a taper machined in the bushing wall. This taper serves to bring about, in the deflected joint, an even distribution of bearing stress between the bushing and the composite socket.

To provide adequate bearing strength for the bolt (bushing) loads, the composition of the laminate at the root-end was carefully chosen using a Kaman finite element code for analysis. The laminate in this area is changed from that of the outboard spar by introduction of additional spanwise unidirectional as well as circumferential and  $\pm 45^\circ$  materials. The result is an essentially isotropic laminate with considerable thickness buildup, to approximately 5 in. (vs 1.5 in. of the nominal spar wall). Fatigue testing of four quarter-scale specimens of this joint, begun in the 150 foot program, was carried on to intentional failure under the Mod-1 contract. Results confirmed the adequacy of the joint for the 30 year design life imposed by the design specification.

#### Materials Selected

The primary structural material of the spar is Transverse Filament Tape (TFT), which was also employed in the 150 foot blade. As the name implies, TFT is a fiberglass tape in which all structural fibers are aligned across the tape width, that is, perpendicular to its length. It is commercially available and has been used for some years in the manufacture of less critical structures such as wound pipe, storage tanks, etc. When wound circumferentially with an overlap, followed by a minor amount of conventional  $90^\circ$  windings to provide compaction and hoop strength, extremely rapid laydown of predominantly spanwise fibers is accomplished.

The TFT material is E-glass, 17 in. wide tape of 36 oz/sq. yd density. The hoop band consists of 64 rovings of S2-glass at 750 yds/lb density; S2-glass is also used in the various reinforcing layers of material added at the root-end. Because of its excellent fatigue properties under adverse environmental conditions, an epoxy resin system is utilized for the spar and for all other bonds in the blade.

Afterbody panels are lightweight sandwich construction, made from 2.3 lb/cu. ft phenolic-impregnated kraft paper honeycomb core faced on both sides with E-glass cloth/epoxy laminates.

The adapter fitting, a weldment made up of forged and rolled sections, as shown in Figure 5, is HY-80 steel. This high yield strength alloy, which was recommended by NASA materials specialists, possesses exceptional toughness, strength and ductility in the as-welded condition without the requirement for stress relief. It is widely used for construction in large, thick section applications such as submarine hulls and missile test platforms.

#### Lightning Protection System

A lightning system was developed by Kaman for the Mod-1 blade. No lightning considerations were included in the 150 foot blade program, so this represented a new technology development. NASA's design specification required a capability of sustaining 200,000 ampere strokes, a very stringent level of infrequent occurrence in nature.

A straightforward and effective approach could have been taken by simply covering the blade with grounded metal screening or incorporating several conductive cables to ground. However, it was considered desirable, in this wind turbine blade, to seek a more optimized approach in order to minimize cost and also to preserve the inherently low electromagnetic interference of composite blades. The latter feature would have been severely compromised by incorporation of an excessively large, metallic conductive system.

Consequently, a development program was carried out in conjunction with a lightning test laboratory, Lightning and Transients Research Institute, St. Paul, Minnesota, in which a full scale portion of the blade was tested. This included long arc strokes on the unprotected specimen, applied and photographed to identify the discharge paths which lightning strokes would take during a natural occurrence. Stroke current was kept low enough to permit repeated tests without incurring damage. These tests demonstrated that lightning protection is needed for composite blades.

A protection system was devised and installed, in stages, during subsequent long arc tests to determine the minimum configuration that eliminates discharge paths inside either the spar or afterbody cavities, since this is the critical condition which must be avoided. The final protection system thus developed, shown in Figure 6, was successfully subjected to the high current, 200,000 ampere strokes without damage.

The protection system configuration consists of a metal tip cap incorporating a short flange, or skirt, on the outside of the blade. This is connected to a single conductor cable of flattened copper braid, which is mounted along the entire trailing edge and is connected to ground through the steel adapter fitting. The copper strap is imbedded in plastic to effect a resilient attachment to the blade so as to prevent load pick-up by the strap during blade bending. A shield is



provided at the inboard end, consisting of a Thorstrand<sup>®</sup> covering on the outside surface of the blade root, extending just outboard of the extreme end of the adapter fitting inside the blade. Thorstrand<sup>®</sup> is a woven cloth of aluminized glass fibers. This shield, which was not included in the developmental test program, was added as a means of preventing a build-up of pre-stroke streamers emanating from the adapter fitting within the spar, which could provide an inside path to ground for a lightning stroke attaching at the blade tip. Kaman's experience with lightning tests of helicopter blades indicates that such a shield can be effective in this manner.

It should be noted that although the system is considered substantiated for a single, high amperage stroke, the repeatability of the system has not yet been substantiated. Kaman has proposed additional testing to determine the amperage level which can be repeatedly sustained; to date this portion of testing has not been contracted.

## MANUFACTURE

### Blade Elements

Figure 7 depicts the various elements which comprise the Mod-1 composite blade, consisting of: spar; afterbody panels; miscellaneous closures and wraps; inboard adapter fitting; lightning protection; and paint. Manufacturing of these areas is discussed in the following paragraphs.

#### Spar

Construction of the spar is carried out as a single stage winding operation, utilizing a large, lathe-like machine. This system and process are illustrated in Figure 8. The primary tooling member is the winding mandrel, Figure 9, mounted as a semi-cantilever beam. Designed by Kaman as a steel weldment, this mandrel represents a departure and considerable improvement over the winding system of the 150 foot blade. The latter used a steady-rest support at approximately mid-span; this, along with the method used for spar removal, necessitated winding the 150 foot spar in four separate stages, each requiring the complete sequence of winding and curing.

Manufacturing the Mod-1 spar involved thirteen winding passes, each laying down a TFT layer followed by the hoop roving band for compaction, Figure 10. Certain of these winding passes were varied in length to produce wall thickness taper, a simple matter with the TFT winding process as compared with conventional filament winding. Additional broadgoods and TFT layers were locally introduced at the inboard end by hand layup between spanwise runs. The spar was cured using portable oven sections, assembled over the total spar, and a hot-air heating system which produced the 180° - 250°F curing temperature. Each cured spar, weighing over 18,000 lbs, was released from the mandrel by a hydraulic jack system which exerted approximately 1.5 million pounds of force against the bucking ring to loosen the cured spar.

The entire winding process for the first spar required 5.5 days, shortened to 4.5 days for the second spar. Considerable further reduction in this process would result from elimination of the extensive hand layup through implementation of production methods. Also, the use of the 36 oz/sq. yd TFT necessitated resin preimpregnation, involving pressure/vacuum cycles in a special tank to ensure full wetting of the transverse roving bundles. Kaman has experience in utilizing a lighter weight TFT in its more recent 40 kW wind turbine blades, with considerable shortening of the winding process resulting from elimination of prewetting.

#### Afterbody

The six curved panels were fabricated by use of an adjustable bond fixture, shown in Figure 11. This tool consists essentially of a caul plate which can be reset for each panel assembly to provide proper curvature and twist. For each panel, the preimpregnated glass cloth outer skin was first layed up on the caul, followed by the lightweight honeycomb core material; the panels varied from 3 in. to 1 in. thickness for each spanwise set. The inner skin was then layed up, followed by curing of the panel assembly in an autoclave at 250°F.

The afterbody panels were assembled to the spar using the same bonding fixture developed for the 150 foot blade. This consists of a series of formed wooden cradle headers, modified for the Mod-1 contour, and a movable upper steel frame which reacts forces exerted by pneumatic hoses in bonding the lap joint of the outer panel skin to spar. The inner skin was bonded to T-clips which were preassembled to the aft wall of the spar; the T-clips themselves were layed up as two individual angle legs. Bond pressure for the clip-to-panel joint was applied by use of temporary backing plates drawn tightly into place by mechanical fasteners.

The remaining step in the panel installation consisted of injecting the syntactic foam material through temporary holes in the outer skins.

#### Closures and Wraps

The trailing edge closure consists of a three-ply cloth layup over the full length, cured under vacuum pressure.

Panel-to-panel joints take the form of large ten-ply overwraps which comprise full circumferential bands around the spar and afterbody. Five such bands were required by NASA as a secondary means of retaining the afterbody in the event of any loss of integrity in the panel/spar joint.

The inboard closure member is a flat panel, built as a skin-honeycomb-skin sandwich in the same manner as the afterbody panels. Edge closure of the triangular panel utilizes seven layers of cloth doubler material; this build-up serves to carry afterbody secondary loads forward into the spar.

### Adapter Fitting

As shown in Figure 5, the steel fitting is constructed as a weldment in three sections, a forged ring and two rolled rings, the latter being 1.25 in. and 1.5 in. thick. Welding was multiple-pass shielded arc.

The end bolt circle, being critical for field attachment to the Mod-1 rotor hub, was drilled using a drill template. An identical template was provided, and checked by NASA against the actual hub in Boone, North Carolina, as an additional dimensional confirmation of this essential joint.

The adapter fitting was installed into the spar end using optical tooling for alignment of the fitting axis with respect to the spar quarter-chord axis, and for pitch orientation. Used as a reference in this process was a template placed inside the spar at the three-quarter blade span station. By means of this system, the two blades were matched to within  $0^{\circ}1.6'$  angularly, and  $0^{\circ}3.6'$  in pitch.

Epoxy adhesive was injected into the voids around the fitting, once it was aligned, to act as a liquid shim to ensure an intimate fit of the adapter in the as-wound spar socket. Temporary bolts were then used to hold the fitting in place while the main bolt/bushing holes were drilled. This consisted of locating and boring each hole to final size and perpendicularity with respect to the adapter fitting. A Bridgeport boring head was mounted on the adapter fitting for this process. The bolts were torqued by means of a hydraulic torque wrench, using measured bolt stretch as the criterion for achieving proper tension.

### Lightning Protection System

Each tip cap was built as a sheet metal, welded assembly fitted to the blade end. The trailing edge ground strap was constructed of a flat-tened braided copper tube, around which was molded a thermoplastic coating using a platen press. The plastic-encased strap was then bonded to the underside of the blade, at the trailing edge, and over-wrapped with a two-ply cloth layup. The Thorstrand<sup>®</sup> layer at the in-board end of the spar was wound in-place during the spar fabrication process.

### Paint System

All portions of the blade are protected with an epoxy primer and polyurethane top coat. This paint system has been found effective in helicopter blade use to protect against environmental attack, including the ultraviolet sunlight influence on resin.

The outboard one-third of the leading edge has a built-up heavier layer of the polyurethane outer coat, to a thickness of 8 - 10 mils. Again based on helicopter technology, this material and thickness have been found to provide effective protection against erosion due to sand and rain impingement.

## TESTING

Developmental testing carried out to date under the Mod-1 program consisted of:

- Full-scale spar buckling
- Quarter-scale fatigue, adapter-to-spar joint
- TFT laminate material characterization, static coupon
- Weight and balance, finished blades.

The weight and balance measurement, noted above, established the total weight and spanwise CG only, chordwise CG having been determined analytically. Results of the measurements were:

Blade No. 1	25,698 lbs at sta. 354.9
Blade No. 2	26,846 lbs at sta. 360.2

The weight difference of 1,148 lbs is larger than had been anticipated analytically from variations to be expected in the weight of components. The growth is considered primarily due to increased resin content observed in the second spar. A different technique for resin application and squeeze-out had been employed during a portion of the second spar's winding process. The result shows that spar weight is much more significantly influenced by the resin application technique than had been anticipated. For production spar winding, this point should be carefully addressed, and manufacturing means and procedures developed to insure consistent resin application.

Mass balancing to bring the CG difference within specification limits has not been carried out for the blades at this writing. It is anticipated that this will take the form of composite material added internally at the tip end of the spar of Blade No. 1; mass balance will be determined in conjunction with the natural frequency testing to be conducted at a future date. The added mass must be of a non-conductive material due to the lightning consideration.

### Tests Planned

Certain further testing and pre-deployment tasks were included under the contract but are currently being held in abeyance by NASA due to funding uncertainty. These include:

- Static bending of finished blades: proof testing to critical limit loads in flatwise and edgewise modes
- Installation of permanent instrumentation: bending strain gage bridges inside of spar
- Calibration of instrumentation
- Natural frequency determination: flatwise and edgewise.

## BLADE COSTS

In assessing the significance of the recurring costs expended for the Mod-1 blades, certain special considerations should be noted.

First, the two blades were built on soft tooling and used shop methods suitable to the manufacture of two articles only. Thus, much hand labor was employed in lieu of automated methods; an example is the hand lay-up of approximately 140 layers of broadgoods for local reinforcement at the spar root-end. For the afterbody panel installation, the critical location and orientation of the T-clips was accomplished without locating or holding fixtures. Hole preparation of the adapter-to-spar hardware was done entirely without drilling fixtures or gauges, necessitating dial indication for perpendicularity and individual diameter measurements for each of the 36 holes. Many other hand operations were employed throughout the blades.

In addition, a considerable amount of manufacturing development and tool tryout was required in building of the first blade. The second blade benefitted from this non-recurring effort and represented a more straightforward fabrication job with a minimum of further development needed. For this reason the second blade is considered the more representative baseline for the cost of the Mod-1 blade.

Records were kept of labor and materials, showing that Blade No. 2 required 5,109 manhours of shop and inspection labor and \$161,000 material cost (1981 dollars). With Kaman's labor rates and overhead burdens applied, the cost was \$307,000, or \$11.40/lb. For comparison purposes, the 150 foot composite blade, described earlier, cost \$14.50/lb (in same year dollars).

A projection of the Mod-1 cost-per-pound was made for a manufacturing run of 100 blades of the present design. This included the effect of learning curve slopes derived for each element of the blade, based on Kaman's helicopter rotor blade experience. Also introduced were the effects of modest production tooling and handling equipment. The result is a \$5.70/lb cost for the 100th blade. This projection is conservative and considered readily achievable for this blade design.

It is recognized, however, that certain features of the design represent cost drivers; these resulted from NASA's requirement to retain the design approach used in the 150 ft blade, and from the special need for equivalence with the steel Mod-1 blades. The former includes such design areas as the bolted adapter fitting and the built-up afterbody assembly. More production-oriented methods have been demonstrated to improve these areas, with attendant cost reduction. For example, Kaman utilized a molded-in-place foam afterbody for the blades now operating on the Company's 40 - 65 kW wind turbine. Production methods of fabricating this type of afterbody, including the introduction of fiberglass skins over the foam, can be accomplished in a one-shot manufacturing procedure. Regarding the inboard attachment fitting, its configuration totally depends on the initial design of the blade-to-hub joint; much can be done to simplify such a connection, resulting in possible

elimination of the need for a fitting altogether, or at least the discarding of a multi-bolt connection to the spar tube.

It is believed that this type of redesign will effect a reduction on the order of 25 - 35%, in the production cost of a 100 ft blade while still retaining all the benefits of composites described earlier.

#### CONCLUSIONS

- As the result of this program, two composite blades have been successfully produced, meeting the Mod-1 interface requirements, which will permit operational evaluation of the benefits of composites for large wind turbine blades.
- The anticipated potential of composites for reducing manufacturing and life-cycle costs in WECS blades continues to be borne out as the result of the work of this program.
- Analytical methods developed for the 150 foot blade, and refined for the Mod-1 blades, are adequate for design of operational blades.
- Similarly, the manufacturing techniques developed in both blade programs, particularly the TFT approach for applying composite materials, have been successfully utilized to produce operational blades. The method of resin application in the spar winding process will require further development in production to ensure consistent spar weight control.
- It has been determined that lightning protection is necessary for an all-composite blade. An effective protection system has been developed which meets NASA's 200,000 ampere stroke requirement.
- Cost of the Mod-1 Blade No. 2 was \$11.40/lb in 1981 dollars, using soft tooling and many hand operations. Production methods and quantities would potentially reduce the cost level to approximately \$5.70/lb for the 100th blade.
- A number of cost drivers have been identified which are amenable to design improvement within the present state-of-the-art, and which could further reduce production costs by 25 to 35 percent.

#### REFERENCE

Gewehr, H. W., "Design, Fabrication, Test, and Evaluation of a Prototype 150-Foot Long Composite Wind Turbine Blade," DOE/NASA/0600-79/1, NASA CR-159775, September 1979.

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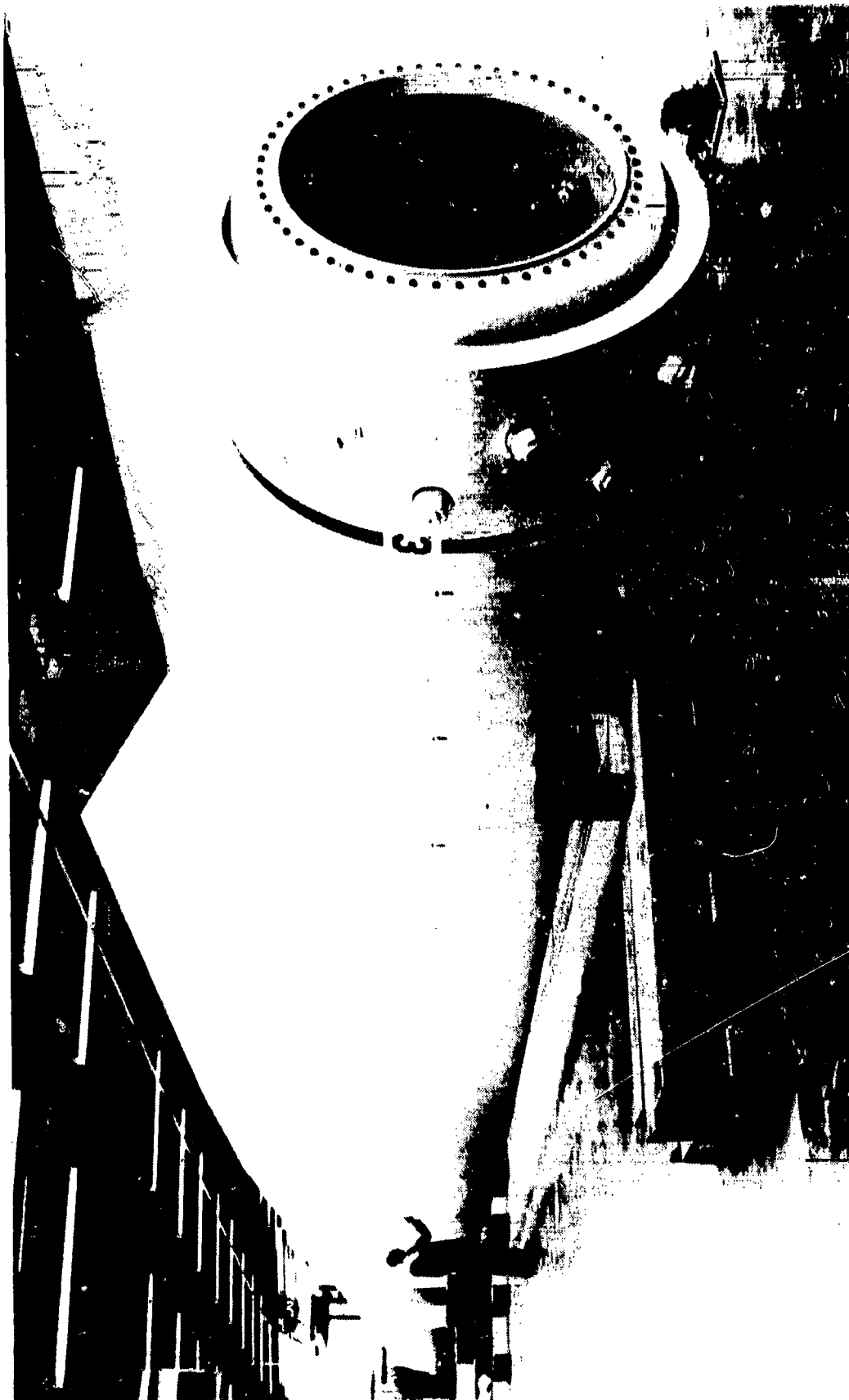


Figure 1. Mod-1 Composite Blade.

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Figure 2. 150 Foot Composite Blade.



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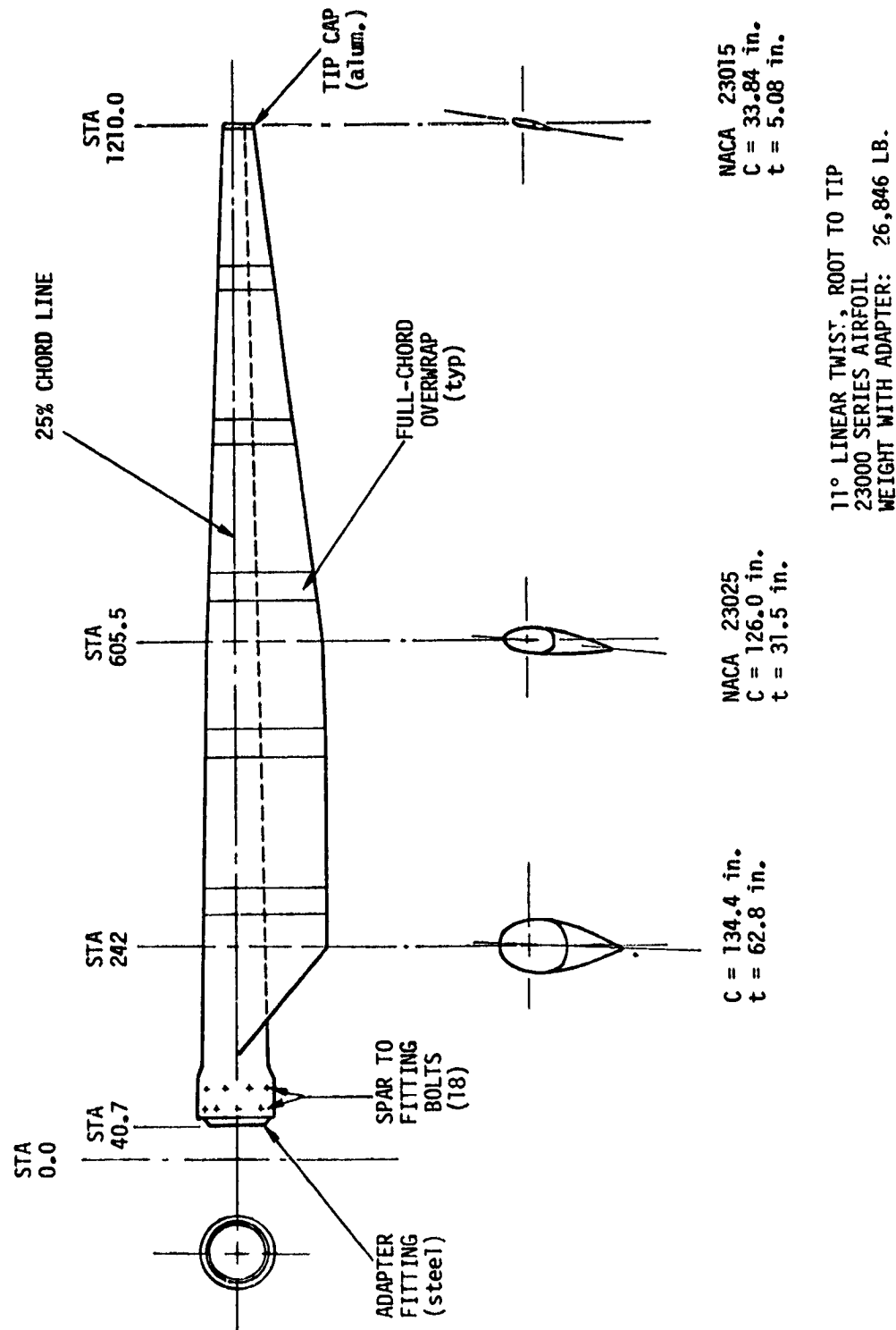


Figure 3. Planform, Mod-1 Blade.

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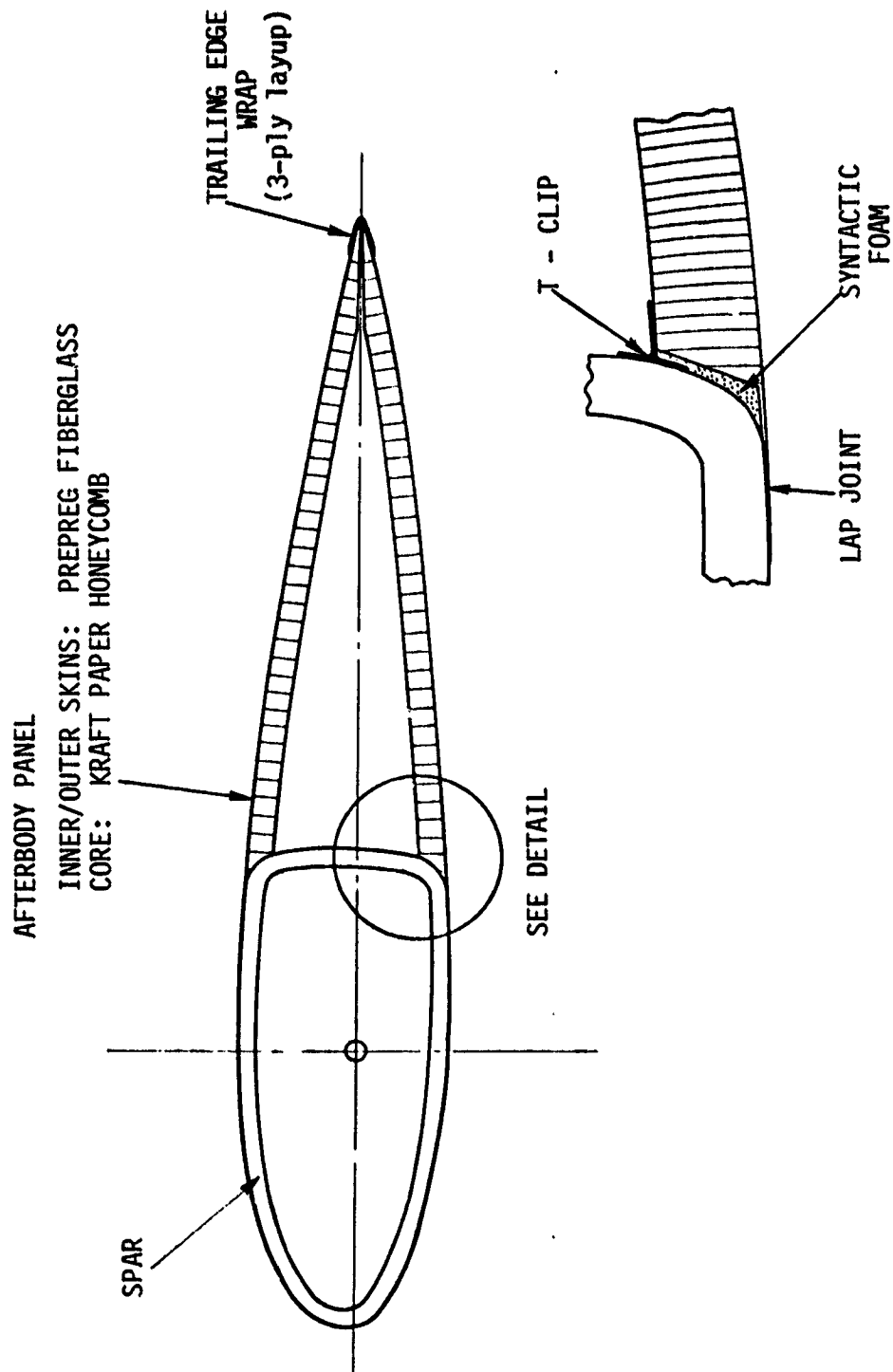


Figure 4. Cross Section, Mod-1 Blade.

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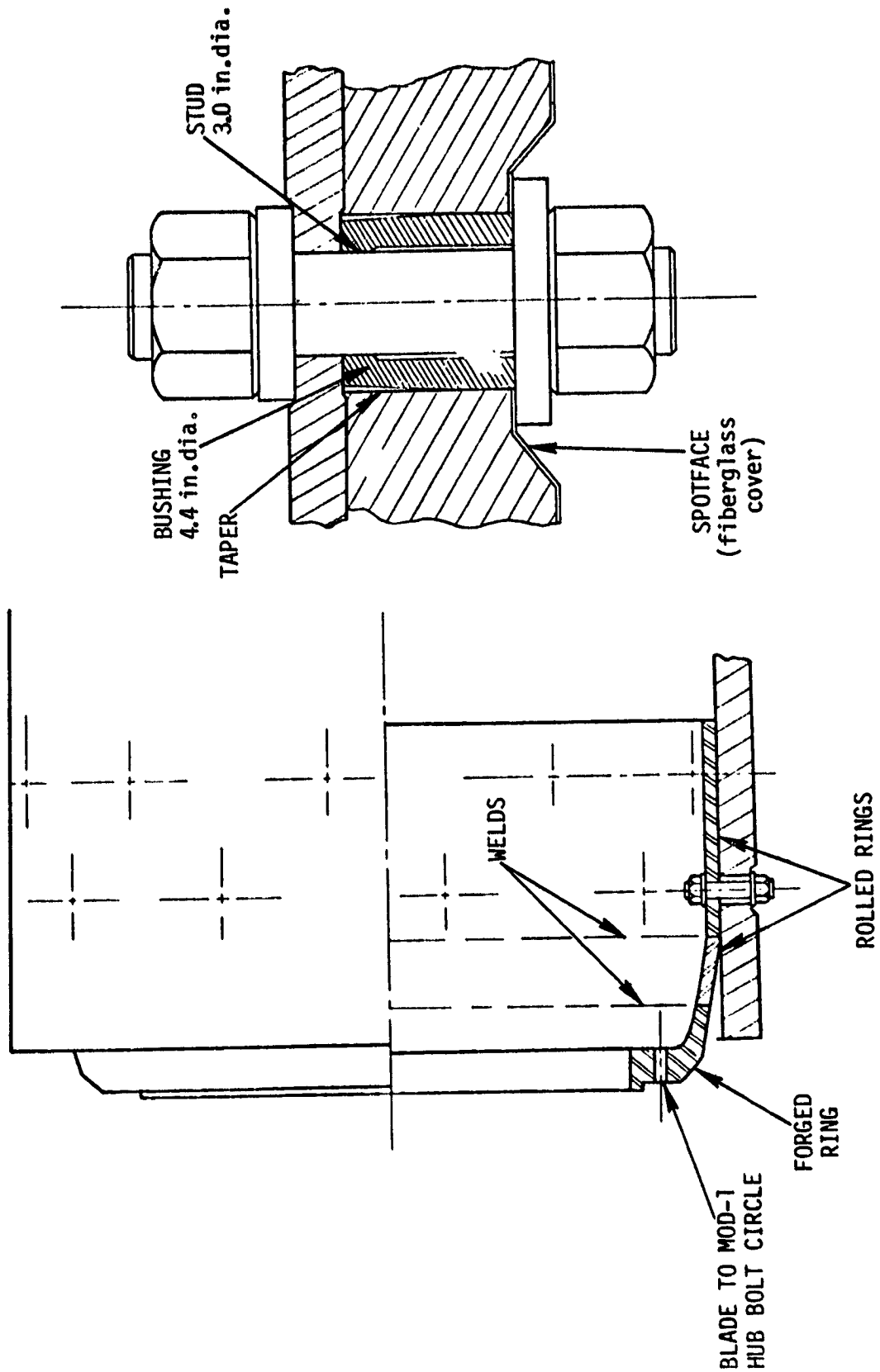


Figure 5. Inboard Adapter Fitting.

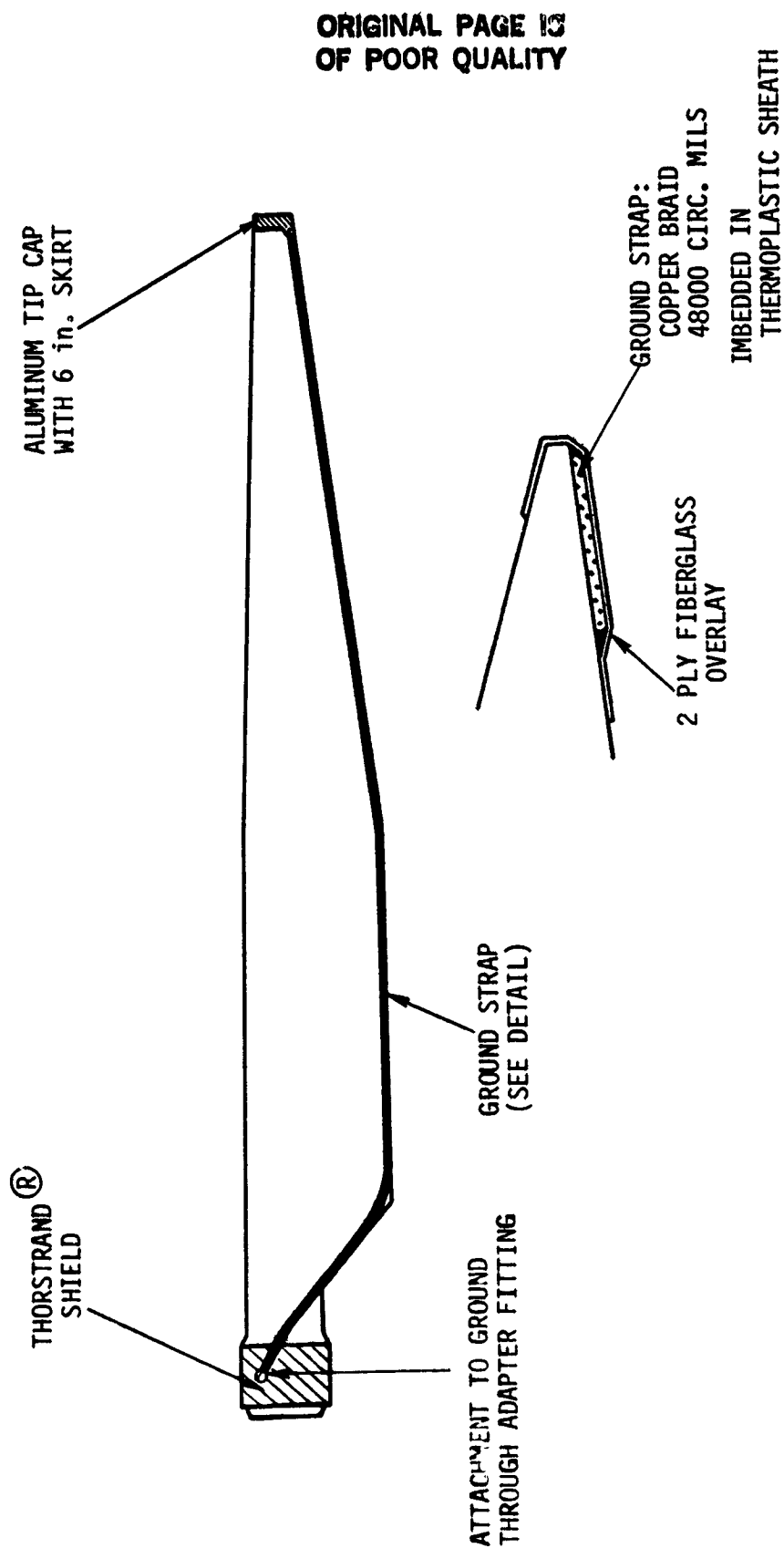


Figure 6. Lightning Protection System.

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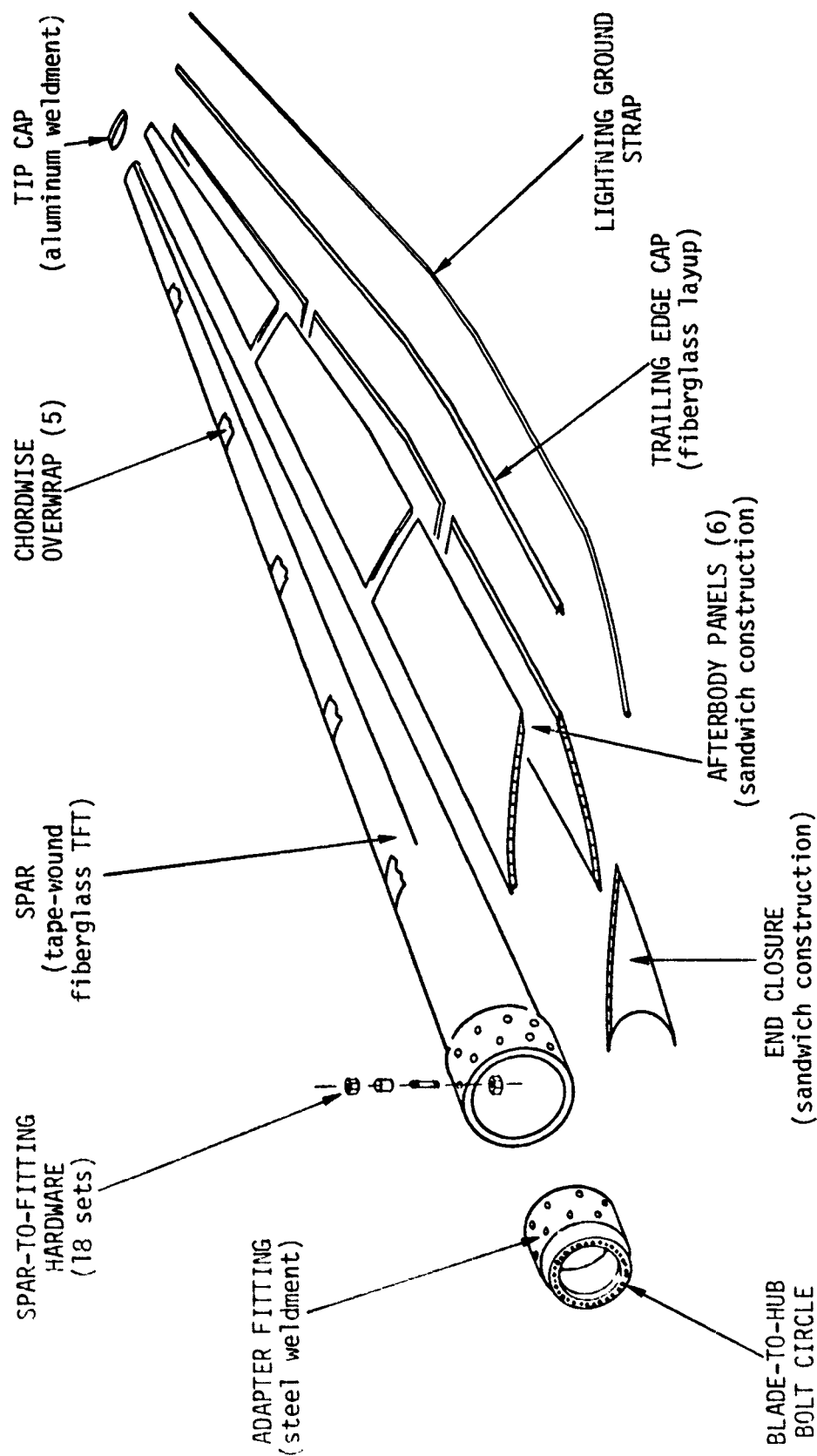


Figure 7. Exploded View, Mod-1 Blade.

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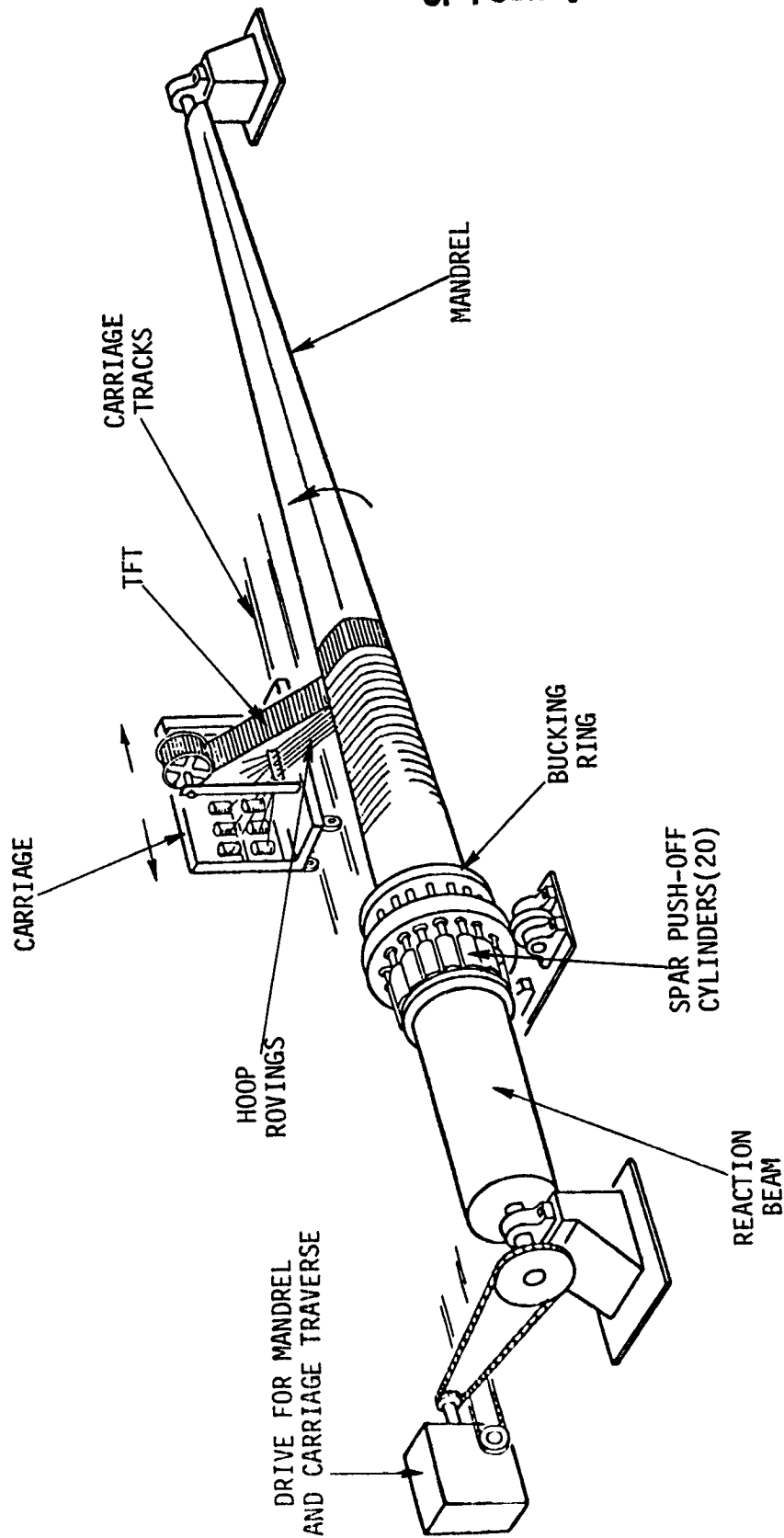


Figure 8. Spar Winding System.

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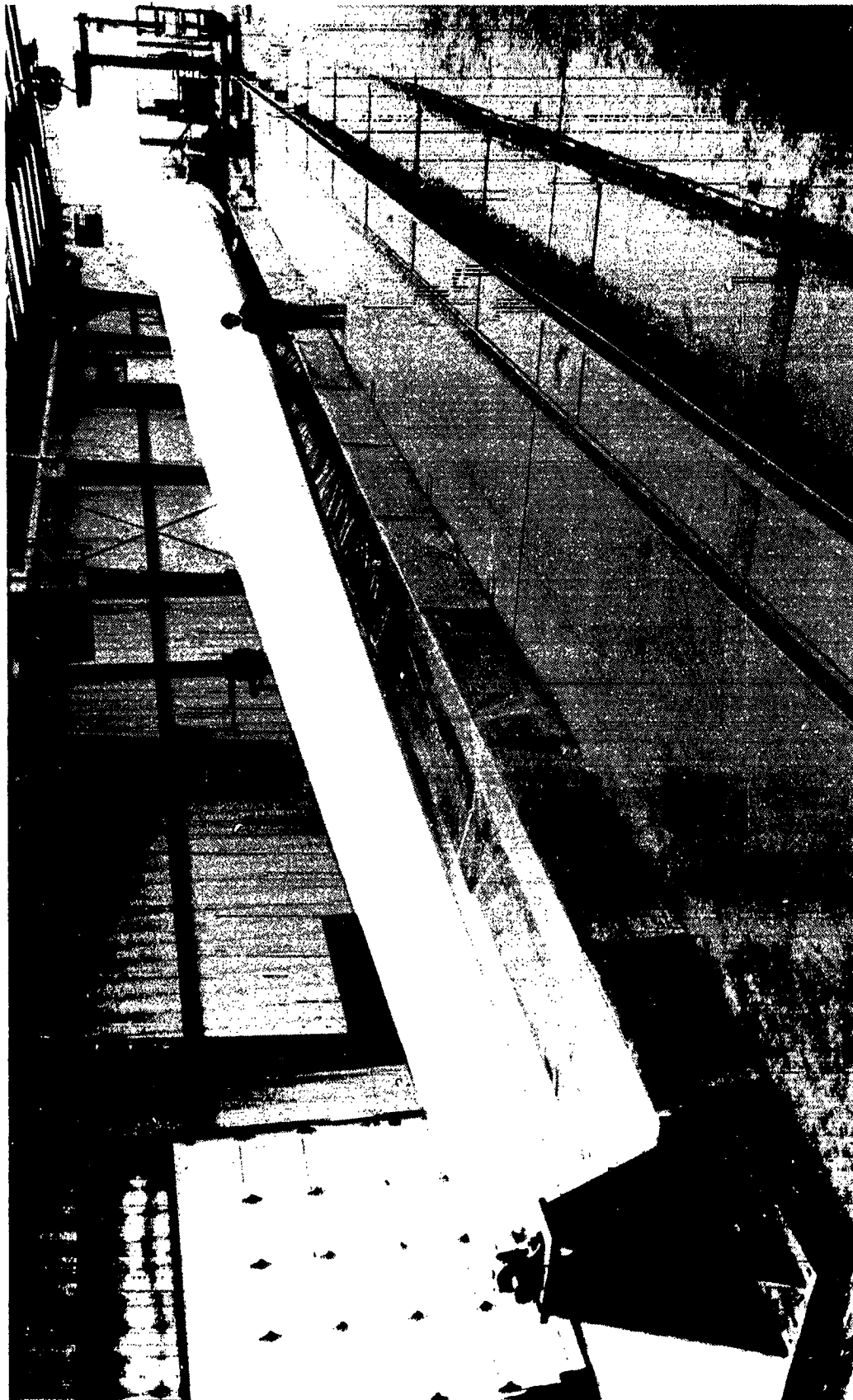


Figure 9. Spar Winding Mandrel.

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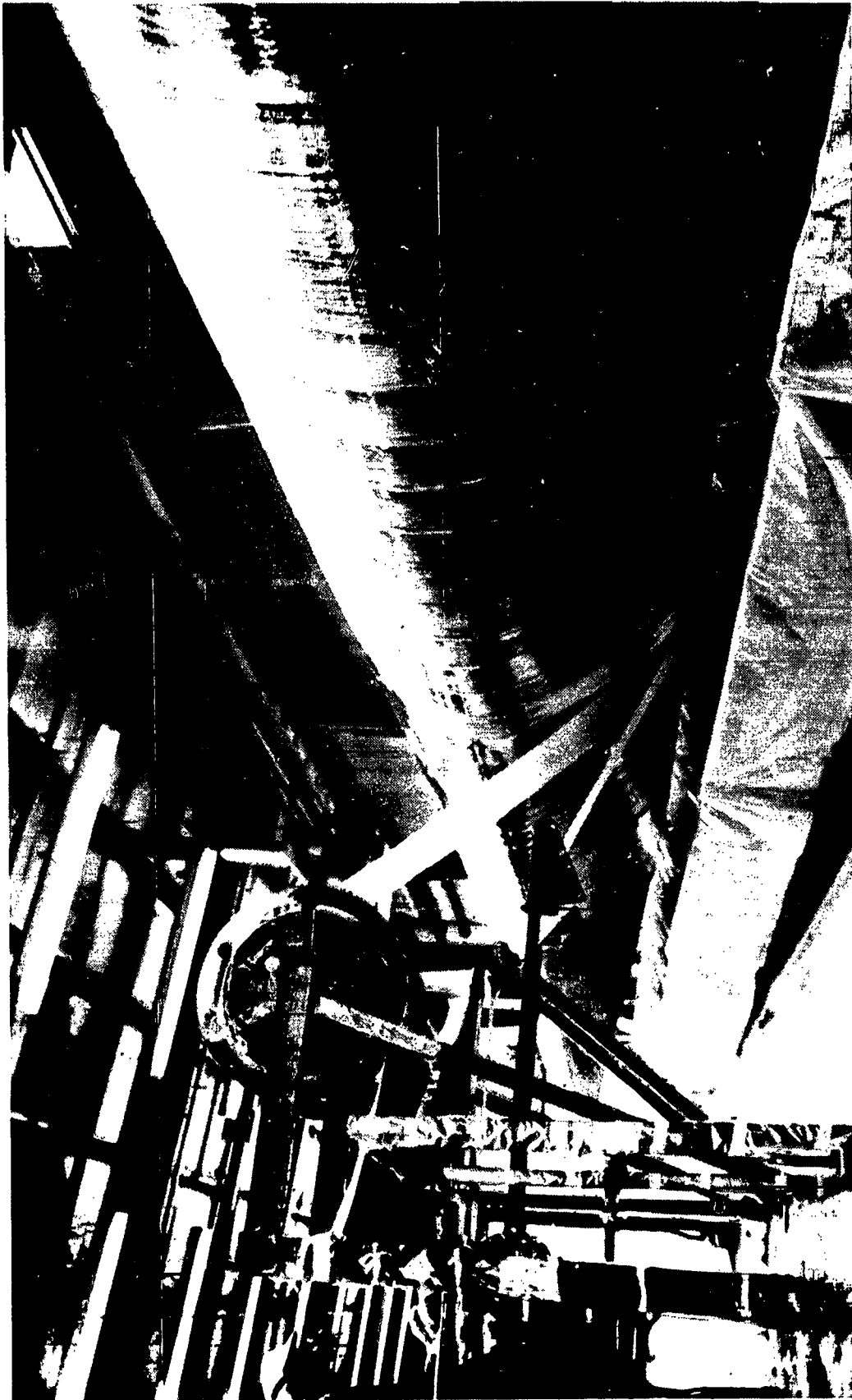


Figure 10. Spar Winding in Progress.



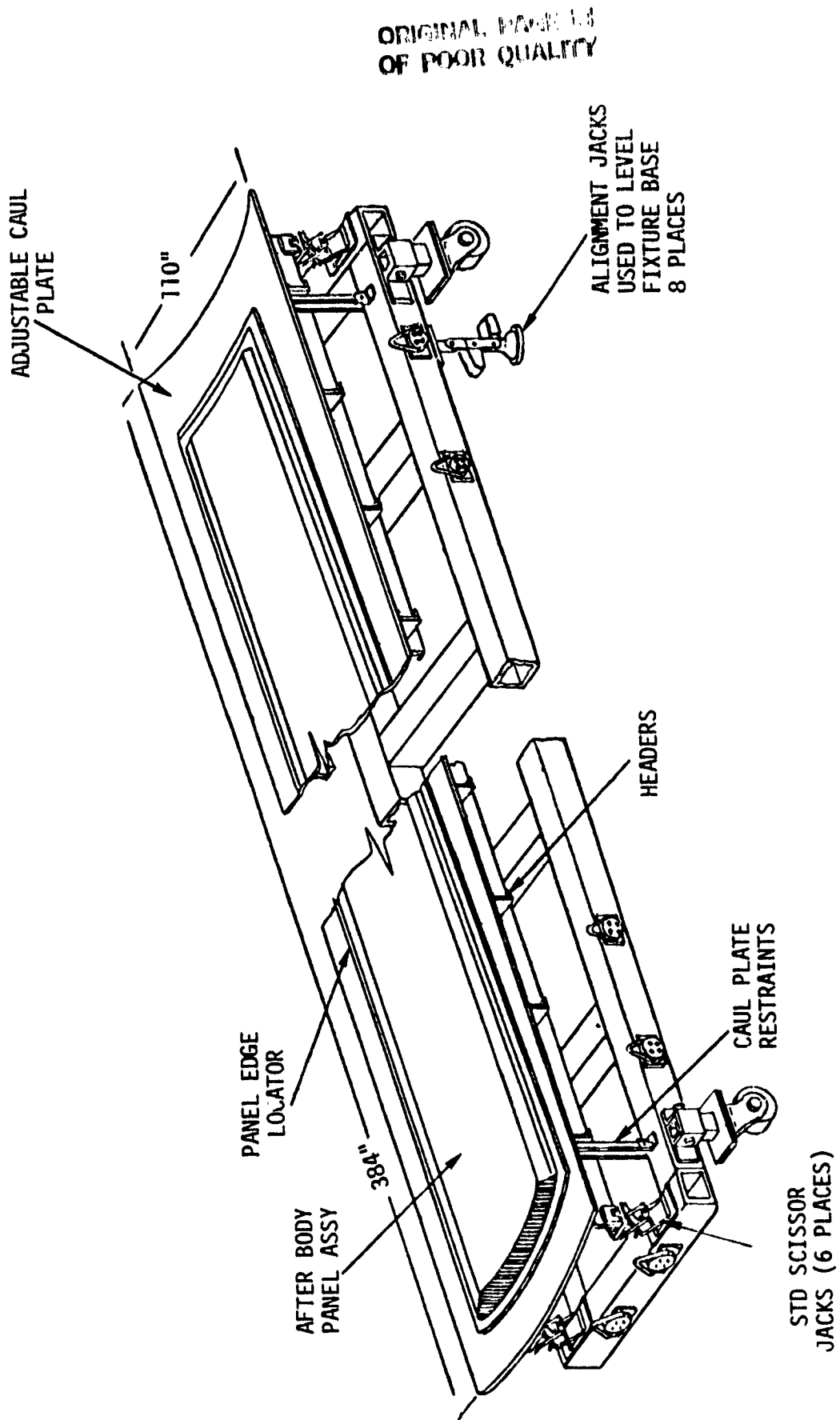


Figure 11. Afterbody Panel Bond Fixture.

QUESTIONS AND ANSWERS

W. R. Batesole

From: P. A. Bergman

Q: In winding the blade span as shown, what type of dimensional tolerances were attainable?

A: *Manufacturing procedures differed somewhat between the two blades in such areas as winding technique and resin application. Therefore, a quantitative level of tolerance control for repetitive manufacture has not yet really been investigated. The built-in twist was compared for the two spars and found to match very closely, although a quantitative value is not available.*

From: F. P. McIlly

Q: Is it really necessary to protect a GRFP rotor blade against lightning? GRFP is an electrically nonconducting material. Are there any experiences from WECs?

A: *The full-scale tests showed that lightning discharges were attracted to the steel hub adapter inside the spar, entering at the tip. Similarly, other discharges occurred through the afterbody panels, "stitching" in and out through the panels from tip to root. High current strokes passing through the inside of a confined cavity in this manner will cause catastrophic damage to the blade.*

## LOW-COST COMPOSITE BLADES FOR THE MOD-OA WIND TURBINES

O. Weingart  
Structural Composites Industries, Inc.\*

## ABSTRACT

This paper describes the Low-Cost Composite Blade Program, carried out by Structural Composites Industries, Inc. (SCI) under contract to NASA-Lewis Research Center (NASA), (funded by the Department of Energy), involving design, evaluation and fabrication of a pair of composite rotor blades for the MOD-OA wind turbine. The objectives of the program were to identify low cost approaches to the design and fabrication of blades for a two-bladed 200 kW wind turbine and to assess the applicability of the techniques to larger and smaller blades.

## SUMMARY

Rotor blades represent a substantial portion of the cost of intermediate to large-size wind turbines. Therefore, low-cost blades are needed to improve the overall cost effectiveness of these systems.

In Phase I of the Low-Cost Composite Blade Program, several blade designs were developed to the point where reasonably accurate estimates could be made of the structural properties and costs of tooling and fabrication. The most cost-effective design was selected for detailed design in Phase II. Structural analysis of the selected design was performed, with assistance from NASA in some of the more specialized techniques (e.g., flutter analysis). Subelement and subscale specimens were fabricated in Phase I for testing by both SCI and NASA. These tests were used to: confirm the physical and mechanical properties of the blade materials; develop and evaluate certain blade fabrication techniques and processes; confirm the structural adequacy of the root end joint design.

\* Now with Rohr Industries, Inc.

In Phase II, blade tooling was designed and fabricated. Two complete blades and a partial blade for tool tryout were built. A patent-pending 100 ft long "ring-winder" machine, designed and built with private funding, was contributed by SCI.

The patented TFT process, developed by SCI and used to fabricate the spar for the DOE/NASA 150 ft composite blade (Ref. 1) was used, in this program, to wind the entire blade. This process allows rapid winding of an axially oriented composite onto a tapered mandrel, with tapered wall thickness. The TFT process thus is uniquely suited to low cost composite blade and spar fabrication.

The ring winder/TFT process combination was used for the first time on this program. This approach allows the blade to be wound on a stationary mandrel, an improvement which alleviates some of the tooling and process problems encountered on previous composite blade programs. The stationary mandrel, with its chordline vertical, is in its stiffest orientation, so deflection is small and constant. The absence of cyclic stresses reduces the chance of premature mandrel failure and assures long tooling life. In addition, doubts about the effect of constant mandrel flexing on the wet or partially cured composite are eliminated.

The low-cost blade adapts to the MOD-OA hub via a bolted circular metal flange. This flange is in an area of maximum steady and cyclic bending moments and shear forces. One challenge in composite blade design is to incorporate such a flange into the composite structure in a manner that facilitates low-cost fabrication while assuring adequate structural margins in this critical area.

In preparation for the low-cost blade program, SCI developed, using private funds, a patented metal hub fitting design which meets the goals stated. The flanged metal fitting is designed to fit over the winding mandrel. It is provided with angular grooves into which the TFT composite is pulled, by tensioned hoop windings, for a mechanical lock. The fitting also contains a bonded transition area where the stiffness gradually transitions from composite to steel.

For redundancy, either the bonded or mechanical joint can accept the full load on the hub. This joint has been thoroughly tested by NASA on two half-scale spars provided during Phase I.

The use of an all-wound blade structure with a wound-in hub fitting, painted and cured in the winding machine, means that the blade is substantially complete when it leaves the winding area. Only minor trimming and assembly operations remain. This approach, with the improvements listed in the conclusions and recommendations section, promises to provide truly low cost composite wind turbine blades in a production environment.

The two 60 ft blades were transported to NASA-LaRC in Cleveland, Ohio from SCT in Azusa, California using one standard extendible 60 ft truck. No crates or special handling fixtures were needed.

The projected cost of production blades in 1978 dollars, built in 100 unit lots, is \$11,745 each or \$4.12/lb. for a 2852 lb blade. This is well within the NASA guidelines.

#### BLADE DESCRIPTION

The final blade configuration, which was designed and analyzed to meet all the NASA design requirements, is shown in the planform sketch of Figure 1. The blade consists of a TFT glass-epoxy airfoil structure filament wound onto a steel root end fitting. The fitting is, in turn, bolted to a conical steel adapter section to provide for mounting attachment to the NASA hub.

A typical cross section of the blade is shown in Figure 2. The blade comprises a 3-cell design configuration containing a leading edge D-spar section followed by a foamed afterbody and a foamed trailing edge cell. The D-spar and afterbody cells constitute the primary structural cells of the blade.

#### ROOT END FITTING

The steel root end fitting is shown schematically in Figure 3. The fitting contains two recessed groove areas to allow mechanical locking of the axial TFT filament wound composite onto the fitting. The locking is achieved by a series of 90° hoop wraps at the groove locations. This SCT patented design approach improves the structural reliability of the joint in the event of adhesive bond failure at the TFT-steel interface.

The gradual taper of the fitting at the outboard edge is designed for smooth load transfer between the spar and the fitting. The shallow conical angle of 4° also facilitates blade manufacturing during the filament winding process. The fitting is circular in cross section to mate to the hub adapter flange and to allow low cost

fabrication by lathe turning of a ring forging. Three Huck-bolts are spaced radially around the circumference to positively prevent blade rotation in the event of adhesive bond failure.

#### HUB ADAPTER

The steel hub adapter for transferring blade loads to the NASA hub is shown schematically in Figure 4. The adapter configuration and in particular the overall length was designed to minimize kick load effects at both the blade hub fitting and MOD-OA hub mounting interfaces. The bolted joint configuration at the hub/fitting interface is designed to facilitate field installation of the blade. The internal bolting surface of the adapter at the hub/adapter interface requires assembly of the adapter to the hub prior to blade attachment to the adapter.

#### BALANCING, ICE DETECTION, LIGHTNING PROTECTION

##### BALANCING PROVISIONS

Forward and aft tubes are provided at root and tip for chordwise and spanwise balancing and tuning. A large tube is provided near the c.g. for matching the weights of blades in a pair. Weight is added by injecting a non-metallic high density filled room temperature curing resin into these tubes.

##### ICE DETECTION

The NASA-furnished ice detector is mounted into a metal recessed flange which is wound into the trailing edge. The wiring conduit is routed along the aft end of the first afterbody wrap. This arrangement allows installation of the detector and wiring without cutting holes in any of the primary blade structure.

##### LIGHTNING PROTECTION

Since the composite blade is non-conductive, it is necessary to provide a conductive path along the blade surface from the aluminum tip cap to the hub fitting to ground any lightning strikes. A 6-in. wide by 0.004-in. thick aluminum foil strip is bonded along the trailing edge and routed to the hub.

## MATERIALS OF CONSTRUCTION

The principal reinforcement is E-glass continuous filament roving which has been woven into transverse filament tape (TFT), bias filament tape (BFT) and longitudinal filament tape (LFT). TFT has the primary filaments transverse to the axis of the tape. When this tape is wound circumferentially around the blade, it deposits the transverse filaments at approximately  $0^\circ$  to the spanwise axis. In an analogous manner, BFT is used to provide  $\pm 45^\circ$  reinforcement. LFT is used to produce  $90^\circ$  reinforcement for chordwise strength. The resin matrix used is the same as that used on the 150 ft composite blade. It is an amine-cured epoxy containing a reactive diluent.

## STRUCTURAL ANALYSIS AND BLADE PROPERTIES

### APPROACH

The analysis utilized both computerized and hand calculations to evaluate the structural integrity of the blade. Computer math models of the blade, hub joint and mandrel were developed and analyzed for stress response and internal load distribution. Hand calculations were then performed to evaluate critical design components based on the internal load distributions. Minimum margins of safety computed for major structural components of the blade are summarized in Table 1.

### ALLOWABLES

#### Strength

The strength allowables used in the analysis are the minimum yield and ultimate strength values known for the materials listed. In the case of the composite TFT and hoop (LFT) material and the adhesive, the yield strength was taken to be 80% of the static ultimate strength of the material. For the adhesive a knockdown factor of 0.75 was applied to the average ultimate strength of the adhesive as reported in the literature for bonded scarf joints to develop the design ultimate strength. In the case of TFT composite spar material, the strength data were derived on the basis of maximum lamina strain theory using a laminate analysis computer program. The resultant failure envelope for the spar material is shown in Figure 5.

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### Buckling

The allowable buckling stresses for the blade were computed according to the expression

$$\sigma_{\text{Calc.}} = 0.314 \left[ \frac{2 - (b/a)^2}{(b/a)^2} \right]^{0.12} \cdot \frac{E_e}{1 - \nu_{12} \nu_{21}} \left( \frac{t}{\bar{r}} \right) \quad (1)$$

where,  $(b/a)$  = Blade Aspect Ratio

$T/F$  = Thickness to Critical Radius of Curvature Ratio

$\nu$  = Poisson's Ratio

$$E_e = \frac{1}{2} \sqrt{E_{11} E_{22}} + \frac{1}{2} \nu_{12} E_{22} + (1 - \nu_{12} \nu_{21}) G_{12}$$

A knockdown factor of 0.45 was applied to Equation (1) to provide design allowable buckling stresses.

### Fatigue

The fatigue allowable for the metal is the minimum endurance limit for notched fatigue strength taken from the literature. This value has been experimentally characterized over a large specimen population and can confidently be used in the blade application.

The fatigue allowables for the TFT composite blade material were determined from the expression

$$S_{\text{MAX}} = \frac{6.20}{1 - .690R} \quad (2)$$

$S_{\text{MAX}}$  = Allowable Maximum Stress

$R$  =  $\sigma_{\text{MIN}} / \sigma_{\text{MAX}}$

$\sigma_{\text{MIN}}$  = Applied Minimum Stress

$\sigma_{\text{MAX}}$  = Applied Maximum Stress

Equation (2) is based on the regression analysis of data from 150 ft spar tests at NASA.

The shear fatigue strength of the adhesive is based on a review of experimental fatigue data on adhesives given in the literature. The value of 1280 psi represents approximately 40% of the yield shear strength of the adhesive. Fatigue endurance limits of this magnitude appear characteristic of single lap shear joint behavior under cyclic loading.



## BLADE PROPERTIES

### Stiffness Distributions

The flexural stiffness distributions of the blade in the flatwise and edgewise directions are shown in Figures 6 and 7, respectively.

### Weight, Center of Gravity and Mass Moment of Inertia

The total predicted weight of the final blade design for structural analysis is 2582 lbs. A breakdown of this weight is shown in Table 2.

The spanwise distribution of this predicted weight is shown in Figure 8. The center of gravity of the blade is located at STA (r/R) = .302. The predicted gravity bending moment of the blade about STA 40 in. is 44,400 ft/lbs.

## COMPARISON TO NASA SPECIFICATIONS

Table 3 summarizes the actual versus NASA specified characteristics of the final SCI low-cost blade design. The only parameter which is out of the specified range is the chordwise center of gravity, which is 38% from the leading edge, against a specified maximum of 32%. NASA analyzed the SCI design for flutter and pitch control forces and determined that the 38% location was acceptable for this particular design.

## MANUFACTURING CONSIDERATIONS

In this section we will discuss manufacturing considerations for the final SCI design.

### FABRICATION PROCEDURES

Figure 9 is an overall flow diagram for the SCI blade.

#### Preparation

The first major step is the process used to vacuum-impregnate the TFT material. The dry tape is unwound into baskets which are placed into a tank for vacuum impregnation. The wet impregnated material is then rewound onto spools which fit the ring winder. The BFT and LFT did not require the vacuum impregnation step, but were wound from the supply spool through a resin bath, and directly onto the ring winder spools.

Other preparation included precutting of the foam cores and the various plies of the web doubler layup, surface preparation and application of release agent to the mandrel.

### Blade Winding

Figure 10 shows the overall winding arrangement for the blades. The water-filled headstock and tailstock support the D-spar mandrel in a fixed position while the traversing ring winder wraps the tape to form the composite. The foam cores are added in succession to form the afterbody and trailing edge.

### Curing and Extraction

The cure oven is rolled over the wound blade from its parked position at the headstock end. A 200 kW electric hot air blower is used to heat the oven.

For mandrel extraction, the tailstock is removed. Four 50 ton hydraulic jacks, driven by a common hydraulic power supply, push against the bucking ring to free the blade from the mandrel. The freed blade, supported by two cranes, is then moved clear of the mandrel while temporary blocks are positioned under the mandrel to support it until the tailstock is replaced.

### Final Finishing and Assembly

The finished blade is painted in the winding machine prior to final cure. The lightning protection strip is applied prior to painting. After extraction, balancing tubes, D-spar rib, ice detector and tip cap are installed to complete the blade.

### QUALITY ASSURANCE

The overall quality assurance flow chart for the low-cost composite blade is presented in Figure 11. Receiving inspection, in-process inspection and final inspection steps are included.

### TOOLING DESIGN AND FABRICATION

Tooling designed for the low-cost composite blade included the winding mandrel and its supports, the tape impregnation equipment and jigs, fixtures and templates for alignment of the blade components during fabrication. The most critical item of tooling was the D-spar mandrel, which is the "backbone" upon which the blade is built.

Structural analysis showed the maximum predicted deflection of the mandrel is less than 1 inch. The maximum skin stress was found to be approximately 5400 psi which is well below the yield stress of the AISI 1020 steel material.

#### HANDLING AND SHIPPING

The blades were shipped on a 60 ft extendible bed truck. The root end fitting was used to support the heavy root end and to take axial acceleration loads. The blades were lifted with a pair of straps centered on the CG.

#### APPLICABILITY TO OTHER SIZES (15 - 200 ft)

No constraint was found in applicability of the LCCB design and fabrication techniques to other sizes. Similar blades have been proposed, studied, designed or built on several other programs in lengths from 15.5 to 250 ft. The filament winding process is not limited to any particular size. (SCI has filament wound large structures such as a railroad car body and a 22½ ft dia x 60 ft long rocket motor case). It is only necessary to provide a large enough winding machine and mandrel(s). Since the composite is being fabricated by the winding process, there is no limitation such as size of available plates or sheets of material. The rovings and tapes used in filament winding are continuous and of practically infinite length.

In the smaller size blades, such as the SCI blades designed for the 4 kW SWECS program, it might be cost-effective to mold the outside surface to final contour after winding. This method is used on helicopter rotor blades. It results in a better contour and surface finish, a denser laminate, and fast cure cycle.

#### RESULTS OF BLADE INSPECTION

The blades were inspected for dimensional accuracy, weight and balance, and finish and appearance.

#### DIMENSIONAL INSPECTION

Measurements were taken of the upper and lower airfoil contours. The total points measured were 96 per blade. The measurements utilized sheet metal airfoil contour templates made from the airfoil mylars.

The results show a mean error for all measurements of  $-.085$  in. This resulted from a general reduction in composite wall thicknesses and foam dimensions due to the vacuum bags used to reduce resin and void content, and the shrinkage of the foam during cure.

The overall accuracy and fairness of the blade contour was adversely affected by the vacuum bagging which tended to pull the wet windings into any low spot in the mandrels, whereas the windings normally tend to bridge and smooth out these places. The effect was especially pronounced in the fairing material used to smooth the transition from foam core to D-spar or first afterbody.

The material was changed from syntactic foam to low density polyurethane foam to save about 100 lbs per blade. This foam-in-place material tended to shrink and soften during blade cure, leaving a spanwise indentation or trough in the outer blade surface.

Another problem encountered was local denting of the trailing edge by winding tension collapsing the foam core.

#### FINISH AND APPEARANCE

The exterior surface finish of filament wound composites is a "natural" finish with some "grain" from the windings. The TFT process uses final passes of  $90^\circ$  hoop windings or LFT to compact the composite and give a lay of the "grain" in the chordwise direction.

The surface finish achieved is estimated to be NASA standard roughness. Appearance, on close up viewing, leaves room for improvement due to the rough finish and the irregularities discussed under "Dimensional Inspection". These problems should not affect blade performance and can be improved on production blades by learning, lower cure temperatures, elimination of vacuum bagging, and the use of "foam in place" cores.

#### WEIGHT AND BALANCE

Table 2 shows an actual versus predicted weight summary of the blades. Within the accuracy of the scale used, the weights of the finished blades, prior to balancing, were identical at 2180 lbs (not including hub adapter). The as built center of gravity was also quite close, within  $1/8$  inch. Both parameters were well within the NASA-specified tolerances of  $\pm 2\%$  (about 50 lbs blade to blade) on weight and  $\pm$  one inch on spanwise c.g. Chordwise c.g. was not checked. Total weight was 10% less than estimated, mostly due to the compaction

achieved by vacuum bagging. These results are encouraging, promising good reproducibility from blade to blade.

## COST AND WEIGHT ANALYSIS

### WEIGHT SUMMARY

The projected weights for the LCCB are listed in Table 3. The 2852 lb projected weight is well below the 3000 lb absolute limit for MOD-OA.

### PRODUCTION COSTS

In Table 4 the costs for quantities of 2 through 1000 production blades are estimated. The assumptions made for these estimates include (1) the use of foam in place cores for the afterbody and trailing edge, (2) a web doubler wound into the D-spar, (3) continuous winding with only one cure cycle and no vacuum bags or peel ply. This modified sequence reduces labor substantially since the cutting, bonding and fairing of the foam cores and the hand layup and positioning of the web doublers on the prototype blades were very labor-intensive, as were the multiple cures, vacuum bags and peel plies.

### COMPARISON TO NASA SPECIFICATION

Figure 12 shows the NASA weight cost envelope with the production version of the SCI LCCB plotted. At \$11,745 and 2,852 lb, it is well within the envelope.

## CONCLUSIONS AND RECOMMENDATIONS

### CONCLUSIONS

- o This program demonstrated a unique and potentially low cost approach to the design and fabrication of blades for a two-bladed 200 kW wind turbine.
- o No technical limitations were found which would prevent the application of the same techniques to blades from 15 to 200 feet in length.
- o The ring winder and TFT process are practical approaches to fabrication of complete large composite multi-cell blades, and eliminate the problems of mandrel deflection, while facilitating the wrapping of an axially oriented composite, with tapering wall thicknesses.

- o The mechanically locked hub flange design is structurally adequate for use in large composite wind turbine blades.

#### RECOMMENDATIONS

The prototype low-cost composite blades were well within the MOD-OA weight and gravity moment restrictions, but were costly to fabricate. Future wind turbines should have hub designs which are coordinated with the blade design to give the lowest possible cost of energy. The following recommended changes in the present design and process could then be implemented:

- o Two cell design with D-spar as the primary load-carrying element.
- o Larger hub diameter to allow extraction of larger mandrel without using a metal root end adapter.
- o Aluminum or mild steel hub fitting for lower cost.
- o Polyester resin for lower raw material and processing cost.
- o Continuous winding process without costly vacuum bag, peel ply and gel between winding steps.
- o Hollow afterbody wound on extractable mandrel. (If foam core must be used in afterbody, then foam in place in a mold).
- o Consider use of modified airfoil with blunt trailing edge.

### NOTICE

The blades discussed in this report were manufactured under one or more of the following U.S. Patents issued to Structural Composites Industries, Inc., Azusa, California:

4,260,332

4,264,278

4,273,601

And other patents pending.

### REFERENCES

1. Kaman Aerospace Company, "Design, Fabrication, Test and Evaluation of a Prototype 150-Foot Long Composite Wind Turbine Blade", NASA CR-159775, September 1979.

# CRITICAL LOADS OF FOUR QUALITY

TABLE 1  
CRITICAL LOAD CONDITIONS AND MARGINS OF SAFETY

<u>Component</u>	<u>Critical Load Condition</u>	<u>Failure Mode</u>	<u>M. S.</u>
Blade Tip Impact with Tower	Shutdown	Deflection	0.06
D-Spar	Shutdown	Tensile	1.13
D-Spar	Survival Wind	Buckling	0.14
D-Spar	Operation	Flatwise Fatigue	0.38
D-Spar	Operation	Edgewise Fatigue	1.67
D-Spar	Operation	Combined Fatigue	0.17
Trailing Edge	Survival Wind	Buckling	0.46
Hub Joint Fitting	Operation	Tensile	0.14
Hub Joint Spar	Operation	Fatigue	0.17
Hub Joint Adhesive	Operation	Fatigue	0.25
Hub Joint Hoops	Operation	Fatigue	1.32
Hub Adapter	Operation	Tensile	1.93
Root End Closure	Survival	Buckling	1.83
Ribs	Operation	Fatigue	2.35

TABLE 2  
WEIGHT COMPARISONS

<u>MATERIAL</u>	<u>TOTAL BLADE WEIGHT (LBS)</u>		
	<u>FINAL DESIGN</u>	<u>AFTER TOOL TRYOUT</u>	<u>ACTUAL BLADE</u>
STEEL HUB FITTING	265	273	
COMPOSITE	1742	1808	
2-LB. FOAM	67	58	
4-LB. FOAM	87	93	
FOAM FILLER	118	21	
ADDITIONAL HARDWARE, PAINT, MISC.	200	105	
TOTAL	2479	2358	2180
HUB ADAPTER	373	373	395
GRAND TOTAL	2852	2731	2575



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TABLE 3  
COMPARISON TO NASA SPECIFICATIONS

	SPECIFICATION	ACTUAL
AIRFOIL	NASA - 230XX	230XX
TWIST	10° MAXIMUM	10°
MAXIMUM THICKNESS, ROOT	40%	30% (.25R)
MAXIMUM THICKNESS, TIP	18%	12%
HUB FLANGE	NASA DWG. CD. 758866 AT STATION 31.75 INCH	SAME (WITH ADAPTER)
PLANFORM	STRAIGHT, STEPPED OR TAPERED	TAPERED
ROOT CUTOUT	MAXIMUM 25%	12-1/2%
LENGTH	60 FT. HUB FLANGE TO TIP	60 FT.
NATURAL FREQUENCIES		
FLATWISE	1.50 Hz -1.85 Hz	1.66 Hz
EDGEWISE	2.15 Hz -2.55 Hz	2.47 Hz
WEIGHT, MAXIMUM	3,000 LBS.	2,852 LBS.
MAX. GRAVITY MOMENT STA. 40 IN.	47,000 LB-FT	44,400 LB-FT
CHORDWISE C.G. FROM L.E.	32% MAXIMUM	38%*
MAX. TIP DEFLECTION	103 IN.	97 IN. MAXIMUM

\* ACCEPTABLE BY NASA ANALYSIS

TABLE 4  
COMPARISON OF PROTOTYPE BLADE COSTS WITH ESTIMATED PRODUCTION BLADE COSTS

NUMBER OF BLADES/YR.	ESTIMATED COSTS PRODUCTION BLADES			ESTIMATED COSTS PROTOTYPE BLADES		
	2	100	1000	2	100	1000
DIRECT LABOR HRS.	201	151	127	2355	785	453
BURDENED LABOR	5025	3775	3175	41729	13900	8022
BURDENED MATERIAL (1)	8383	6275	5295	28823	8602	4964
Total Cost	13408	10050	8470	67552	22501	12986
Fee @ 10%	1341	1005	847	6755	2250	1299
TOTAL PRICE	14749	11055	9317	74307	24751	14285
AMORTIZED TOOLING	34520	690	69	34520	690	69
GRAND TOTAL	49269	11745	9386	108827	25441	14354

(1) Includes Root End Adapter

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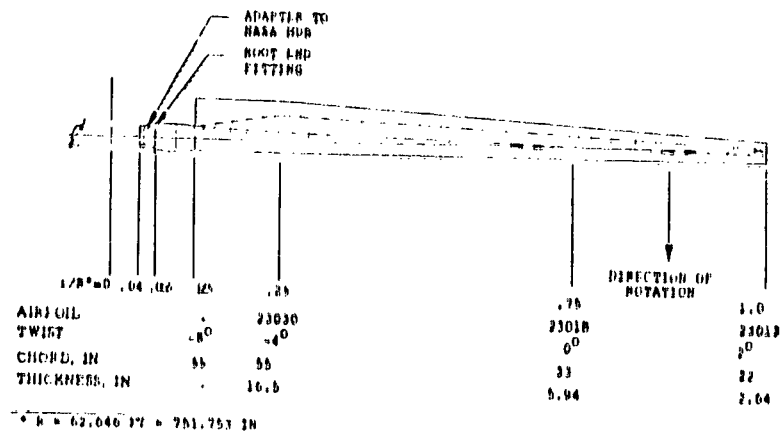
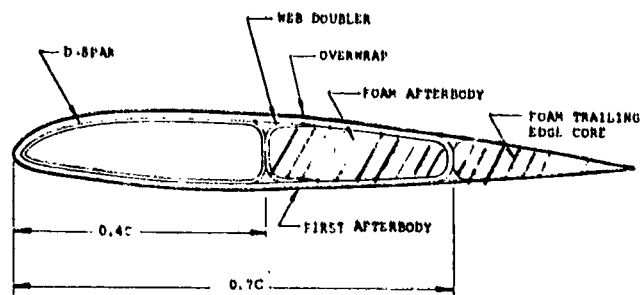


FIGURE 1 BLADE GEOMETRY DEFINITION



STATION .75R

NACA 23018 AIRFOIL

FIGURE 2 TYPICAL BLADE CROSS SECTION

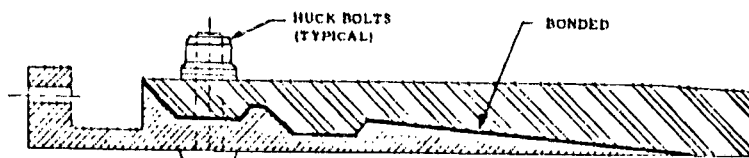


FIGURE 3 ROOT END DETAIL

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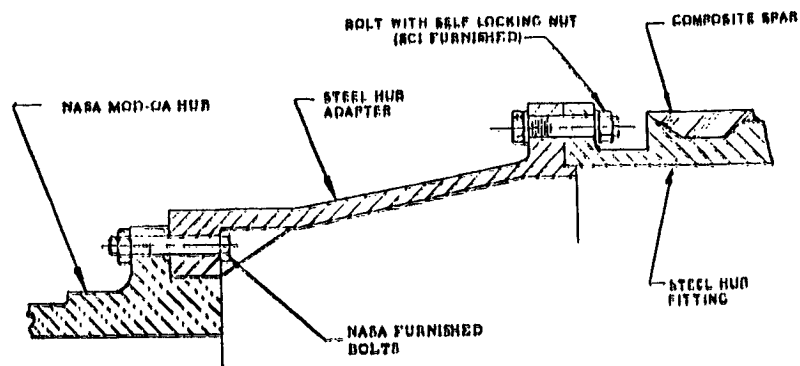


FIGURE 4 HUB ADAPTER DETAILS

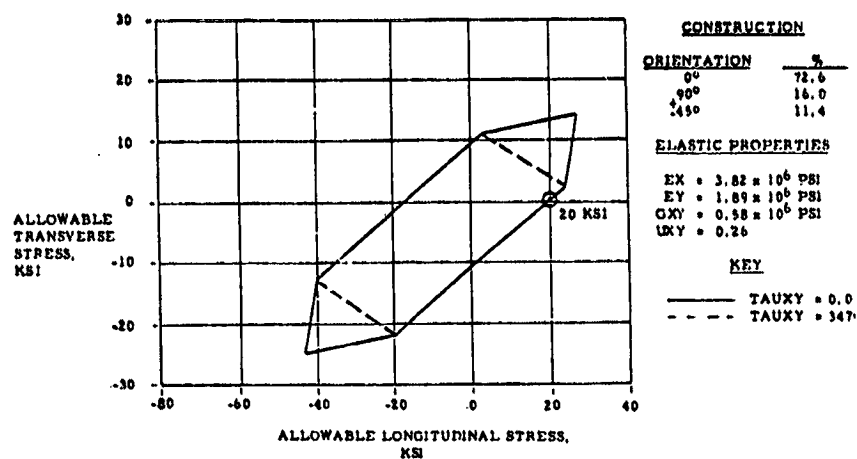


FIGURE 5 COMBINED STRESS ALLOWABLES - TYPICAL SPAR COMPOSITE

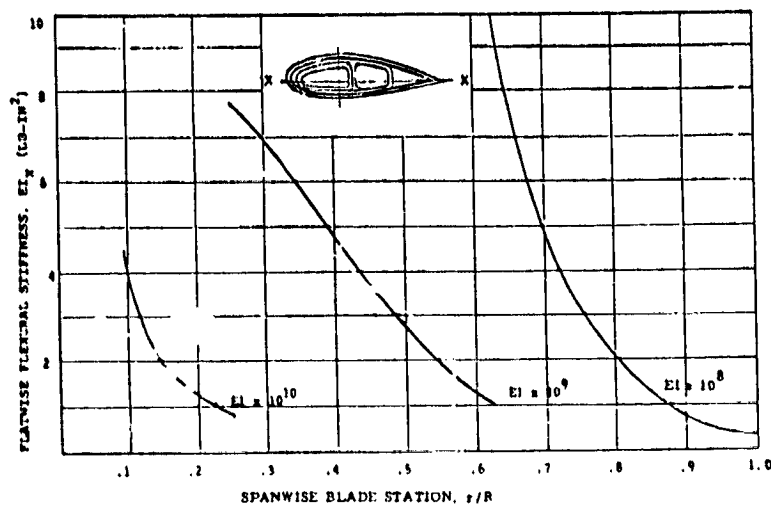


FIGURE 6 BLADE FLATWISE FLEXURAL STIFFNESS

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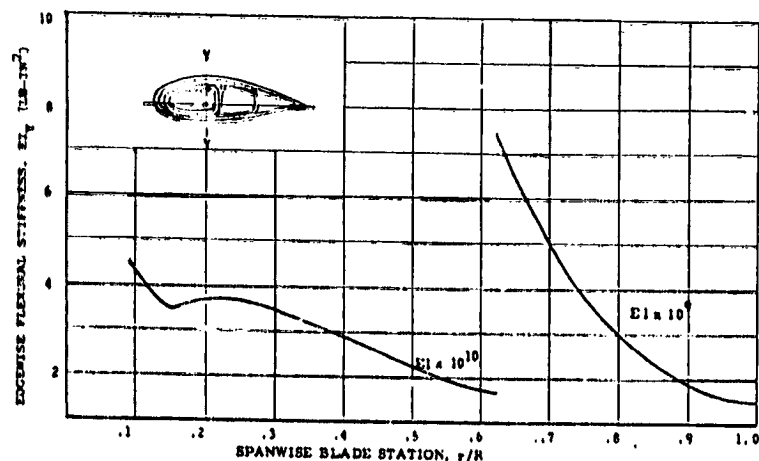


FIGURE 7 BLADE EDGEWISE FLEXURAL STIFFNESS

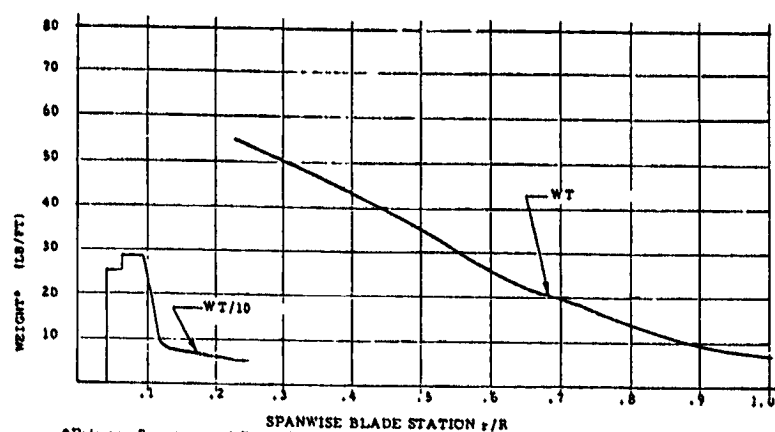


FIGURE 8 BLADE WEIGHT DISTRIBUTION  
\*Primary Structure and Foam Cores

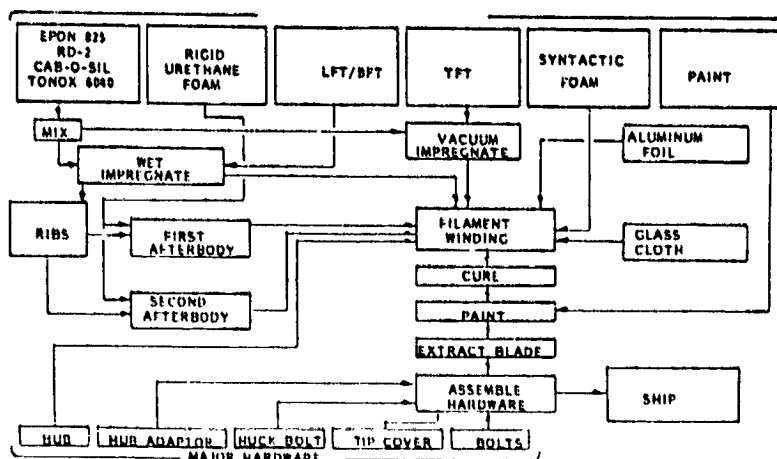


FIGURE 9 FABRICATION PROCEDURE (PROTOTYPE)

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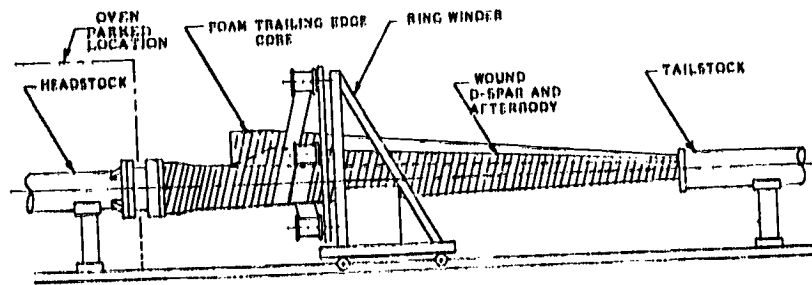


FIGURE 10 MANUFACTURING APPROACH

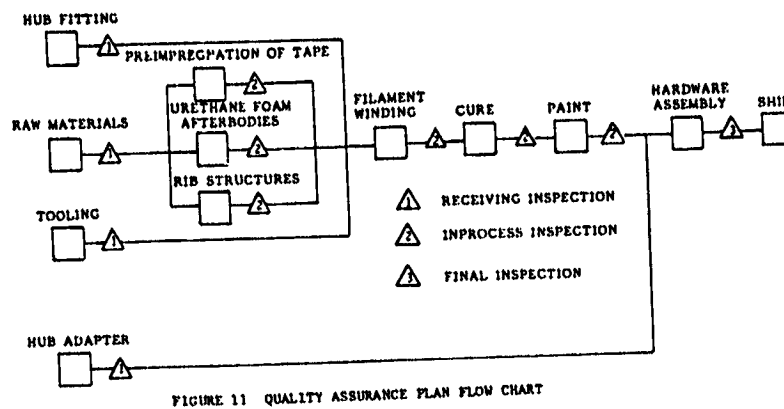
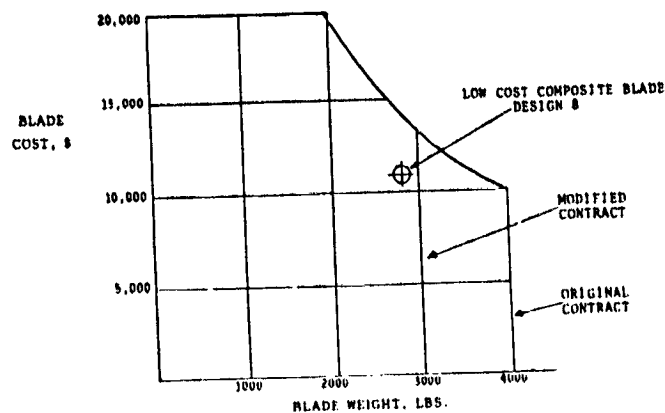


FIGURE 11 QUALITY ASSURANCE PLAN FLOW CHART



(1) 100 BLADES/YEAR, 1978 DOLLARS

FIGURE 12 ALLOWABLE COST/WEIGHT ENVELOPE

## QUESTIONS AND ANSWERS

O. Weingart

From: J. Dugundji

Q: How much overlap did you use when winding the 7 inch tape?

A: *3 to 3½ inches. The strength and modulus of the resulting material is comparable to a continuous filament reinforced composite of similar materials, resin, volume, and fiber orientation.*

From: P. A. Bergman

Q: Did you evaluate building a stiffer mandrel to deal with mandrel deflection, rather than the rotating winding system that was built?

A: *No! This was adequately addressed in the Kaman 100 ft blade and Hamilton Standard WTS-4.*

**FIBERGLASS COMPOSITE BLADES FOR THE 4 MW - WTS-4 WIND TURBINE**

**R.J. Bussolari**  
**Wind Energy Systems**  
**Hamilton Standard Division of United Technologies**  
**Windsor Locks, Connecticut 06096**

**ABSTRACT**

The WTS-4 is a four-megawatt, horizontal-axis wind turbine presently being fabricated for the U.S. Department of Interior, Bureau of Reclamation, by United Technologies' Hamilton Standard division. The blade consists of a two-cell, monolithic structure of filament-wound, fiberglass/epoxy composite. Filament winding is a low-cost process which can produce a blade with an aerodynamically efficient airfoil and planform with nonlinear twist to achieve high performance in terms of energy capture. Its retention provides a redundant attachment for long, durable life and safety. Advanced tooling concepts and a sophisticated computer control is used to achieve the unique filament-wound shape.

**INTRODUCTION**

The Hamilton Standard WTS-4 is a 4 MW downwind, horizontal-axis wind turbine being fabricated for the U.S. Department of Interior, Bureau of Reclamation, for installation at Medicine Bow, Wyoming. The downwind teetered rotor contains two fiberglass blades which span a diameter of 78.1 meters (256.4 ft). The design of the blades was initiated as part of a joint program between Hamilton Standard and Karlskronavarvet in Sweden, to develop the 3 MW WTS-3 for the Swedish government, and was upgraded to meet the needs of the WTS-4.

The blades consist of a filament-wound, fiberglass epoxy structure designed for minimum weight and cost embodying long life and a large margin of structural integrity. They are built by Hamilton Standard at its wind turbine manufacturing facility in East Granby, Connecticut.

**FEATURES**

The WTS-4 blade is shown in Figure 1. The blade consists of a glass fiber composite structure, 38 meters (125 ft) long, joined to two steel retention rings at the blade root. The blade is 15 feet wide at its maximum chord dimension. The diameter at the retention is 6 feet.

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FIGURE 1. WTS-4 FIBERGLASS COMPOSITE WIND TURBINE BLADE

The blade assembly weighs approximately 29,000 pounds, consisting of 19,000 pounds of fiberglass and 10,000 pounds of steel retention hardware. The blade has 23,0XX series NACA airfoil with  $11^\circ$  nonlinear twist and optimum planform for high performance.

The following features are embodied in the design of the blade:

- Monolithic filament-wound fiberglass structure.
- Redundant retention.
- Lightning protection.

Figure 2 shows a cross-section depicting the monolithic construction of the blade. The advantage of this construction is that the simple spar-shell structure has no primary bond joints. This results in an efficient structural shape allowing the optimum use of strong, stiff, light material with continuously variable wall thickness. The two-cell monolithic construction is achieved by first winding epoxy impregnated glass filaments on a spar mandrel, followed by a second filament winding over a shell mandrel with the two sections co-cured forming a single composite structure. Filament winding provides an efficient low-cost process which can be adapted to achieve the optimum airfoil shape, planform and twist needed for high performance and resulting high energy capture.



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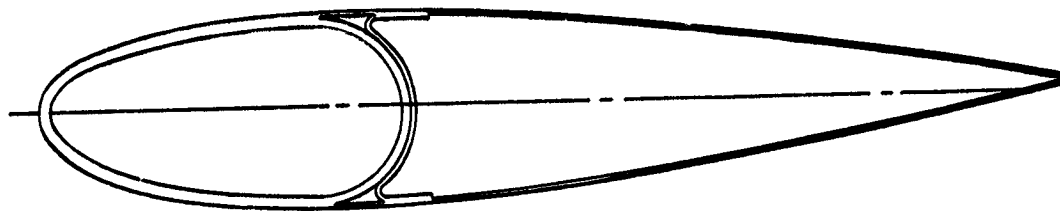


FIGURE 2. CROSS-SECTION OF WTS-4 BLADE SHOWING MONOLITHIC CONSTRUCTION

The retention at the root end of the blade, to provide attachment to the hub, is implemented by two concentric steel rings that are pinned and bolted together, the latter acting as a load transfer point between the fiberglass structure and the rings (Figure 3). The bolted joint is designed to withstand all of the normal and extraordinary loads, both steady and vibratory, expected during the blade service life. Redundancy is provided by bonded joints between the fiberglass and the outer and the inner ring. Each of these joints also is capable of handling all expected loads.

The outer retention rings also serve two additional functions. They provide the seat for the retention bearing and an integral attachment for the dual redundant pitch change actuators.

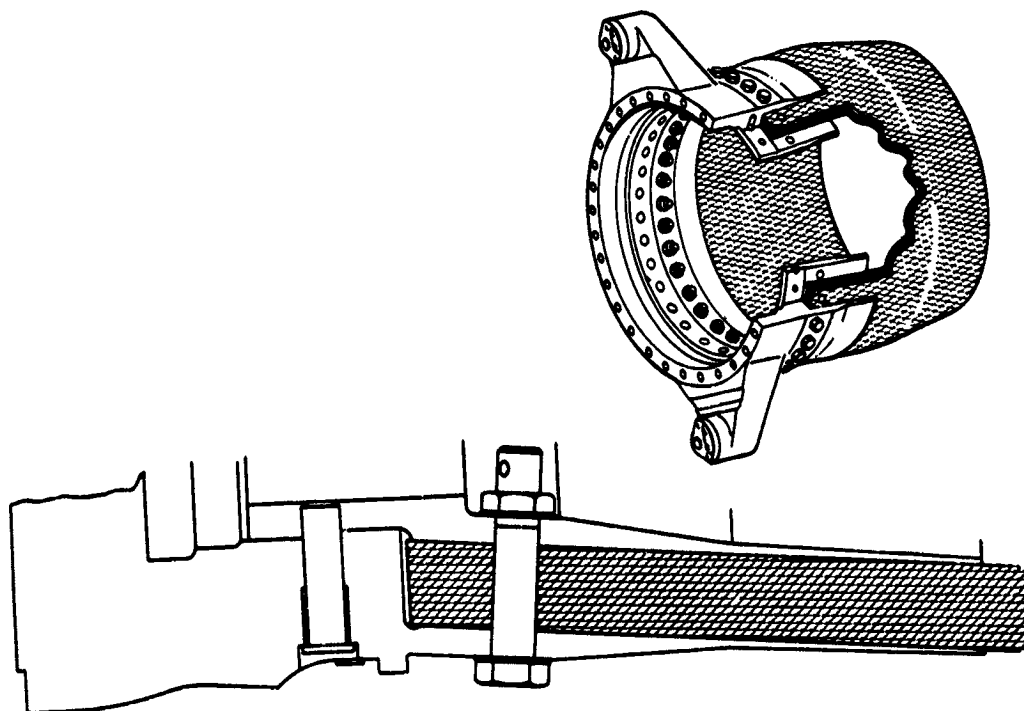


FIGURE 3. REDUNDANT BONDED AND BOLTED RETENTION

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Lightning protection is provided by thin aluminum strips applied on the leading and trailing edges with connecting cross strips, as shown schematically in Figure 4. This system was successfully tested on sample sections from a similarly constructed one-half scale fiberglass blade.

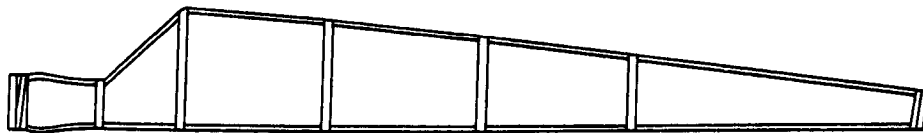


FIGURE 4. THIN STRIPS OF ALUMINUM TAPE PROVIDE LIGHTNING PROTECTION

#### MANUFACTURING PROCESS

The basic filament winding process used to fabricate the composite structure of the blade is widely used in industry to fabricate cylindrical shapes such as rocket casings and high-pressure pipes. A rotating mandrel, previously covered by a release agent, is wrapped by strands of fiberglass filaments which have been wetted with an epoxy or polyester resin. Filament winding noncylindrical shapes, such as the airfoil of a wind turbine blade, requires a unique systems operation of the filament winding equipment.

To provide the correct direction lay of the filaments, multiple axis control of the machine is necessary. Figure 5 shows schematically the operation of this winding process.

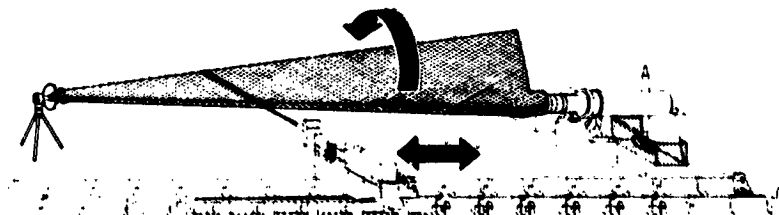
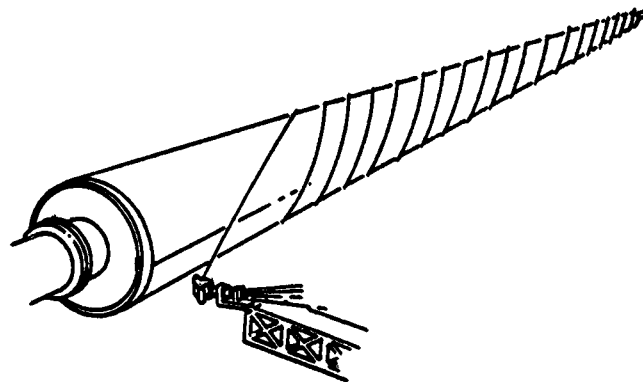


FIGURE 5. THE WIND TURBINE BLADE FILAMENT WINDING MACHINE CONTROLS ALL VARIABLES DURING WINDING

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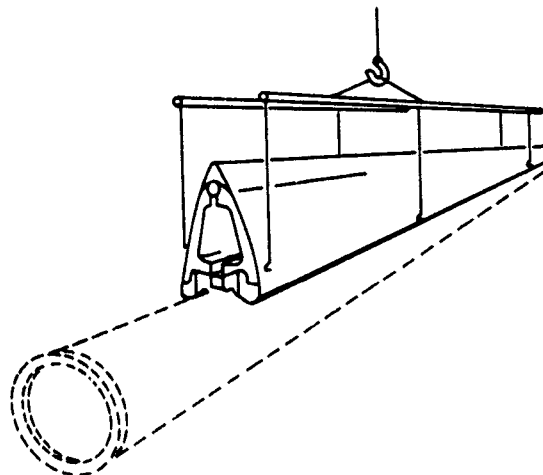
The carriage, containing the spools of fiberglass filament and resin bath, travels along a track parallel to the rotating blade mandrel. All motions of the carriage are computer-controlled to follow the rotational position of the blade. This provides a specially-designed path of filaments. This unique orientation of the fibers creates the specially-designed composite structure. The complete winding of the blade requires over 400,000 program commands. Less than 100 hours of winding time is required. This is equivalent to an average fiberglass lay down rate of 200 pounds/hour.

The process starts by winding a number of layers of epoxy-coated fiberglass filaments on a one-piece spar mandrel, as shown schematically in Figure 6.



**FIGURE 6. BLADE FABRICATION STARTS WITH FILAMENT WINDING OF THE SPAR**

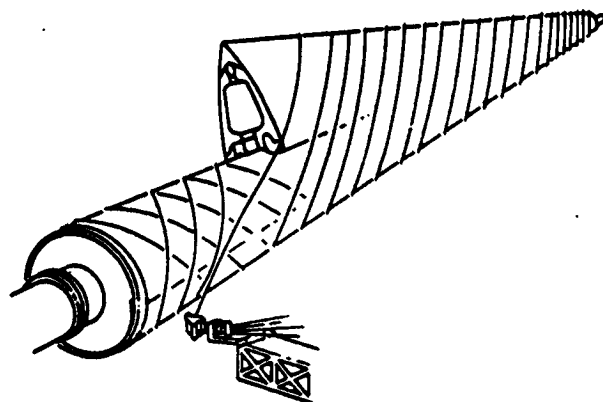
The mandrel is designed to be very stiff to obtain small deflections during operation. After the spar has been wound with the proper number of layers of filaments, it is air-cured briefly. A trailing edge shell mandrel of generally triangular cross-section is then positioned on the spar, as shown in Figure 7.



**FIGURE 7. THE SHELL MANDREL IS MOUNTED ON THE FILAMENT-WOUND SPAR**

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This shall mandrel has an airfoil shape and twist which patterns the final blade shape. It is strapped in place and filament winding is resumed over the assembly. The straps are removed as the winding progresses and the winding continues until the proper number of glass filament layers have been applied. (Figure 8).



**FIGURE 8. FILAMENT WINDING OF THE TRAILING EDGE TAKES PLACE RIGHT OVER THE SPAR/SHELL MANDREL ASSEMBLY**

When the winding has been completed, the entire blade assembly is placed inside an oven and cured for several hours at an elevated temperature. The shell and spar mandrels are then removed. Attachment of the retention rings and bolts, as well as finishing operations, are then performed. Figure 9 shows a completed filament-wound blade before finishing operations in the factory, with another blade being prepared for shell winding.

Large wind turbine blades manufactured in the manner described have inherent advantages. Because the process is automatic, it lends itself to low-cost quantity production. Process variables are few and noncritical, simplifying quality control procedures. The structural characteristics result in long life and practically no inspection and maintenance. High performance is achieved because no compromise is required in aerodynamic planform and twist, and the resulting airfoil shape is smooth, accurate, and repeatable.

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**FIGURE 9. ONE WIND TURBINE BLADE BEING FINISHED  
WHILE ANOTHER IS BEING PREPARED FOR  
SHELL WINDING.**

QUESTIONS AND ANSWERS

R. J. Bussolari

From: O. Weinhart

Q: Can you say what the production cost per pound will be for the filament-wound blades? What reinforcement was used, E or S glass?

A: *Production cost will be four to five dollars per pound. E glass was used for reinforcement.*

## DESIGN AND EVALUATION OF LOW COST BLADES FOR LARGE WIND DRIVEN GENERATING SYSTEMS

W. S. Eggert, Chief Designer  
The Budd Company Technical Center  
NASA-Lewis Contract DEN 3-129

### ABSTRACT

The program task was to develop a low cost blade concept, based on the NASA-Lewis specifications, and to evaluate its principle characteristics, its low cost features, advantages and disadvantages. A blade structure was designed and construction methods and materials were selected. Complete blade tooling concepts, various technical and economic analysis, and evaluations of the blade design were performed. A comprehensive fatigue test program was conducted to provide data and to verify the design. A test specimen of the spar assembly, including the root end attachment, has been fabricated. This is a full-scale specimen of the root end configuration, 20 ft long, and will be fatigue tested by NASA. A blade design for the Mod. "O" system has been completed.

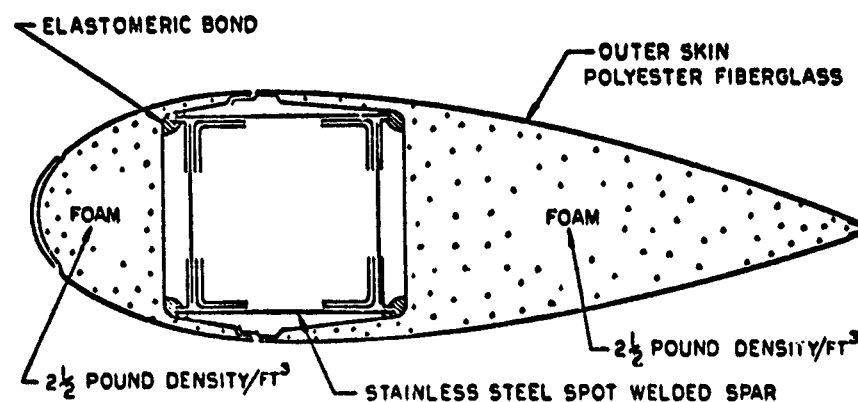
### OVERVIEW OF CONTRACT OBJECTIVES

The design of large wind turbine blades have conflicting requirements and criteria. Cost is the most sensitive requirement and structural reliability is the foremost criterion. The basic design is predicated on the premise that large blades should be an industrial product of predictable performance and uncomplicated structure. In order to be successful, rotors must be capable of being produced in volume at reasonable cost. The Budd Company draws upon its background and knowledge in fabrication of long-life carbon steel and stainless steel structures and mass fabrication of glass-reinforced structural parts. Fabricating techniques combined with a long history of successful product designs assures that the program objectives can be met.

### BUDD DESIGN CONCEPT

In conventional design, the leading edge section, or the D spar area of the blade, is used to carry the operating loads, and the trailing edge is essentially non-structural, carrying air loads for the trailing edge only. The Budd design does not have a conventional forward D spar. The design uses a central spine spar that is essentially non-dimensional relative to the aerodynamic surface; that is, it is a simple, rectangular spar located within the envelope of the aerodynamic contours. This spar carries all the basic edgewise loading and all the basic flatwise loading and provides primarily all the torsional stiffness for the blade system.

The leading edge and trailing edge fiberglass components are designed to distribute the air loads to spar and are segmented spanwise to prevent them from having to carry high loads in the spanwise direction due to spar bending deflections. These sections are bonded to the spar using an elastomeric adhesive. The illustration is an idealized section cut at station 187 of the blade. There is a center spar composed of spot welded stainless steel. This structure is composed of top and bottom cap strips, two shear webs, one on the front and one on the aft side of the spar. This spar is built with a  $10^\circ$  twist from the root end to the outer end. The leading edge and the trailing edge of the assemblies are fabricated of fiberglass reinforced plastic composed of multiple pieces that are then filled with urethane foam. These fiberglass subassemblies are bonded to the spar at the four flange corners of the spar. The leading and trailing edge assemblies are also bonded and mechanically fastened at the high camber point of the blade. The leading edge of the blade is protected by an elastomeric sheet to provide energy absorption due to impact of hail and other abrasive elements. The leading and trailing elements are designed so as not to contribute significantly to the structural stiffness of the blade.

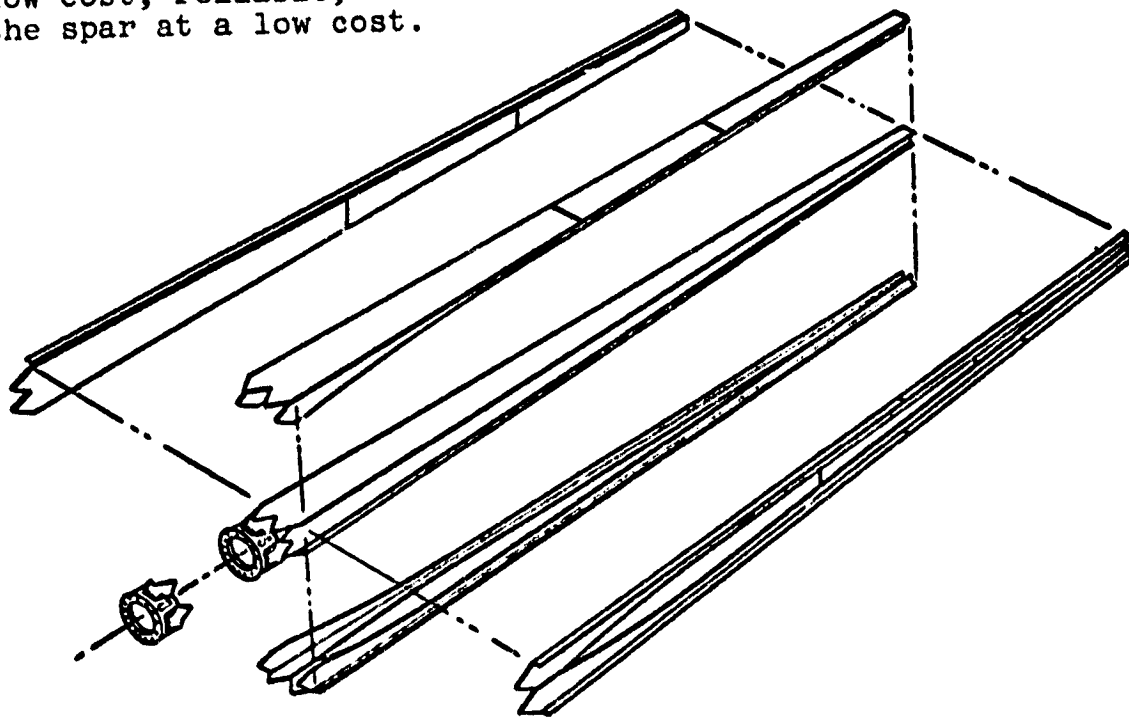


TYPICAL SECTION  
WIND TURBINE BLADE



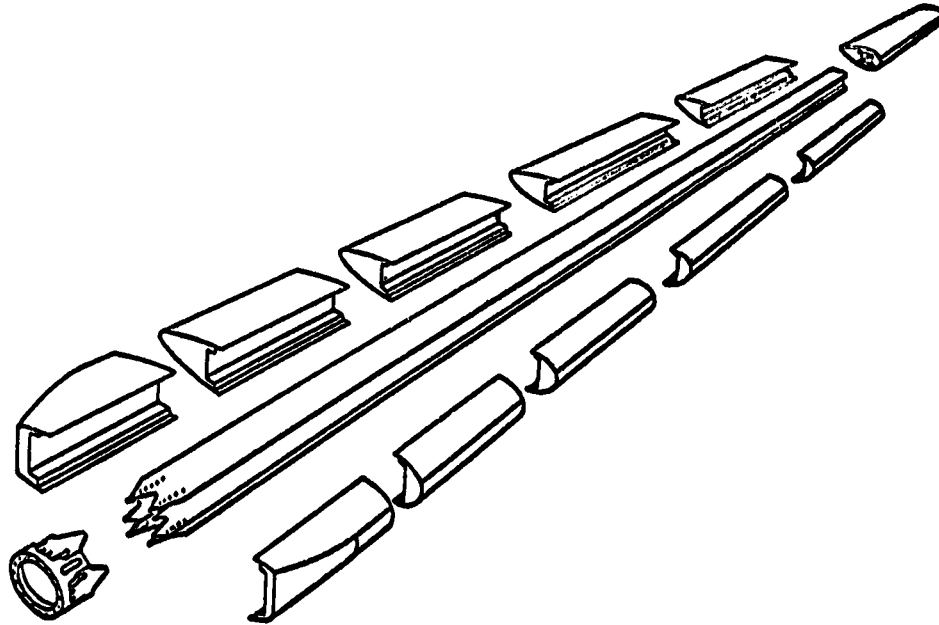
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Shown is an exploded view of the spar assembly. The spar is composed of four sub-assemblies, an upper and lower cap strip plate assembly and a front and rear spar web assembly. The selection of stainless steel and the spot weld process provides a unique method by which the spar stiffness can be effectively tapered to provide a near uniform stress from the root end to the tip of the spar. This tapering is accomplished by the use of tapered angles that are spot welded together and are joined to the upper and lower cap strip plate. The thickness of the top plates are tapered in three steps using a butt arc weld to join each thickness. This is a specialized process that was developed during the Budd 301 testing program. This provides a weld of high reliability in fatigue strength. By controlling this taper, we are able to provide uniform tapering of the basic properties of the spar section. The angles are first tapered in the blank and, as a result, there is essentially no material lost. The angles are then formed and then spot welded to the spar cap assembly. This is all done in the flat and then they are elastically twisted to match the  $10^\circ$  twist of the spar. The spar webs are composed of two angles and spar web. The two angles and web are spot welded in place to form the web for the spar. There are two of these. These are also built flat and elastically twisted to form the  $10^\circ$  twist to the spar. The four assemblies are then assembled into an assembly fixture with the  $10^\circ$  twist provided and are spot welded together. This provides a very efficient tapering of the spar without machining and at a very low cost, using rolled sheet material. The use of stainless steel also provides excellent corrosion protection for long life of the spar. Spot welding provides a low cost, reliable, efficient assembly process to assemble the spar at a low cost.



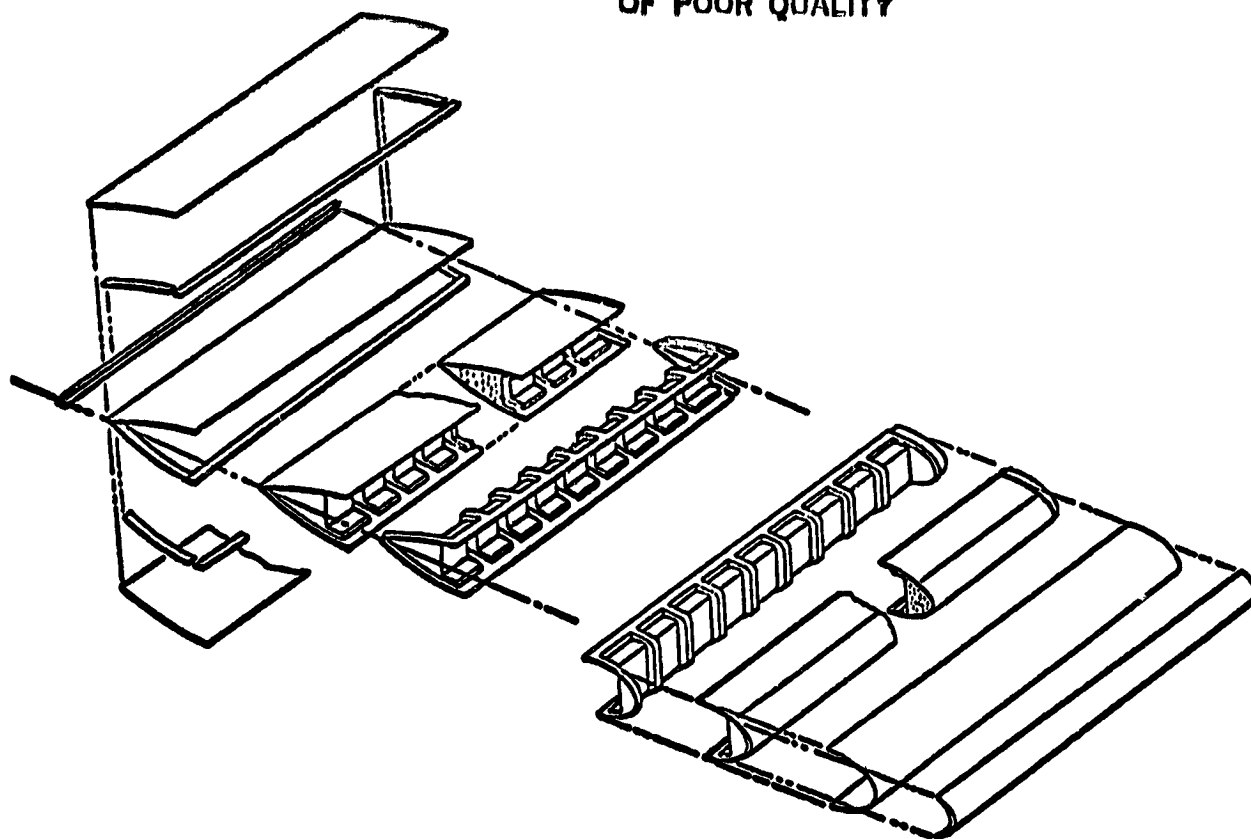
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The illustration shows a breakout of all the major sub-assemblies of the blade.

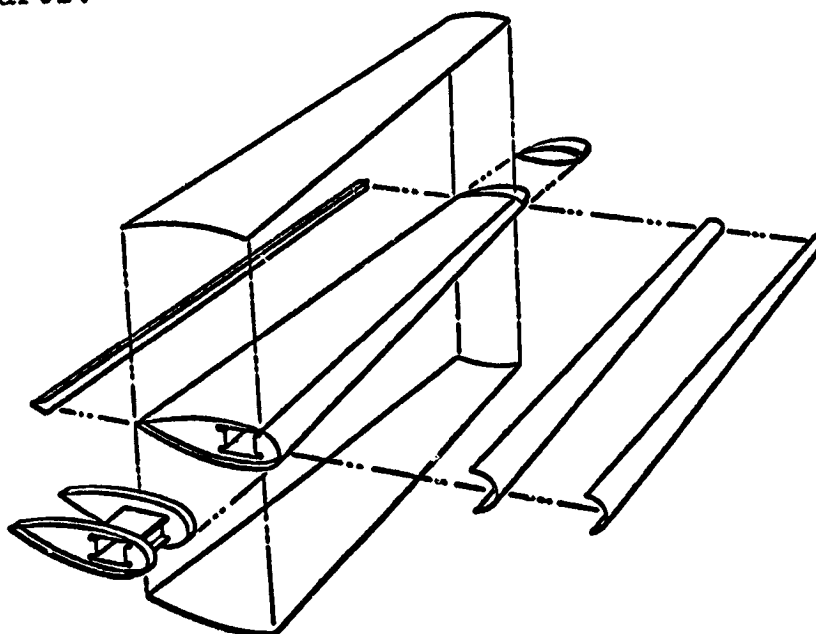


The illustration on the following page shows an exploded view of the leading edge and trailing edge assemblies. These assemblies are composed of low cost layup of fiberglass-reinforced polyester. A commercial grade of this material is used. Fiberglass elements are parasitic to the primary spar structure and are used only to distribute the air loads to the spar. Their design requirements are minimal. To stabilize these elements for fatigue, the fiberglass elements are filled with a semi-rigid, urethane foam of approximately 2 1/2 pounds per cubic foot density. This provides a light-weight, well-damped structure for the leading and trailing edge assemblies and prevents aerodynamic flutter of lightweight surfaces. This design permits accurate dimensional control of the aerodynamic surfaces at low relative cost.

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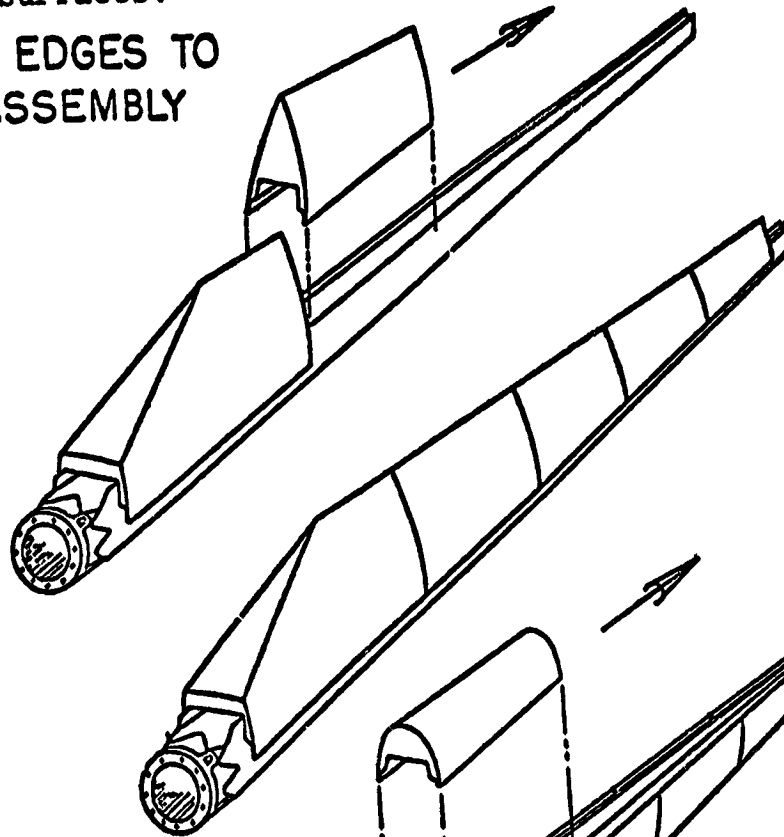
To reduce weight and to improve mass distribution in the blade, the metal spar is cut short and a structural fiberglass tip extension is used. The illustration shows a breakout view of the tip parts.



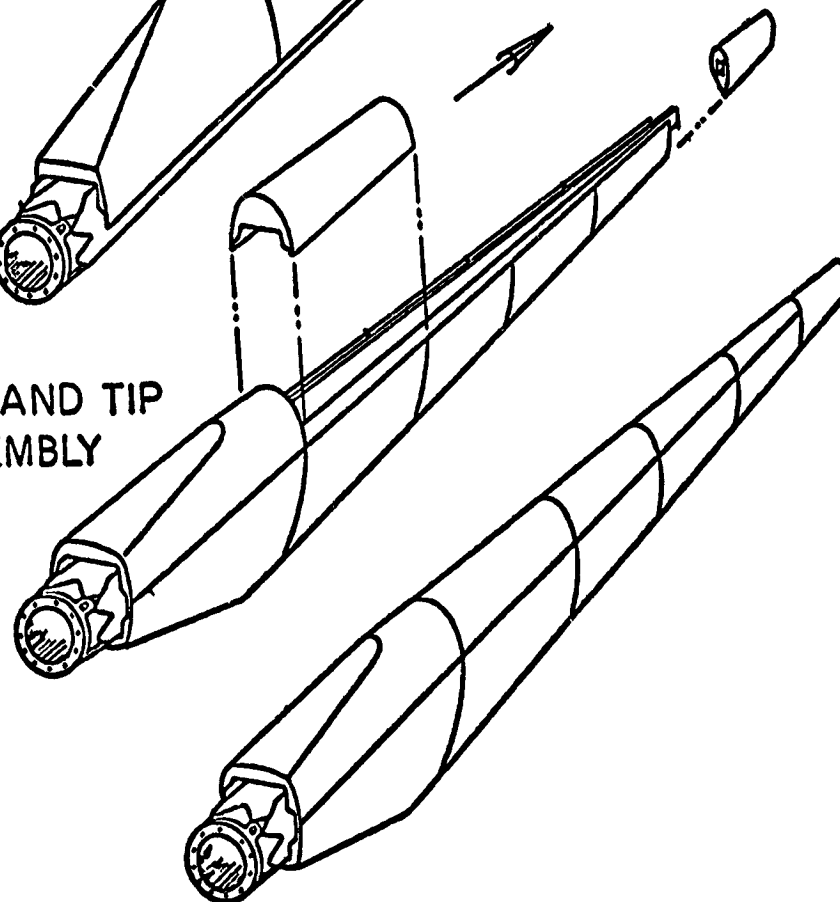
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The final assembly of the blade is accomplished in two major steps. The trailing edge assemblies are bonded to the spar. Working from the inboard end of the blade outboard, the leading edges are then assembled to the spar trailing edge major assembly by bonding and mechanical fastening, working from the inboard end outboard. The tip assembly is then bonded and mechanically joined to the blade assembly. The final step is the installation of elastomeric sealing strips between the edges of the fiberglass assemblies to provide aerodynamic sealing of the surfaces.

TRAILING EDGES TO  
SPAR ASSEMBLY

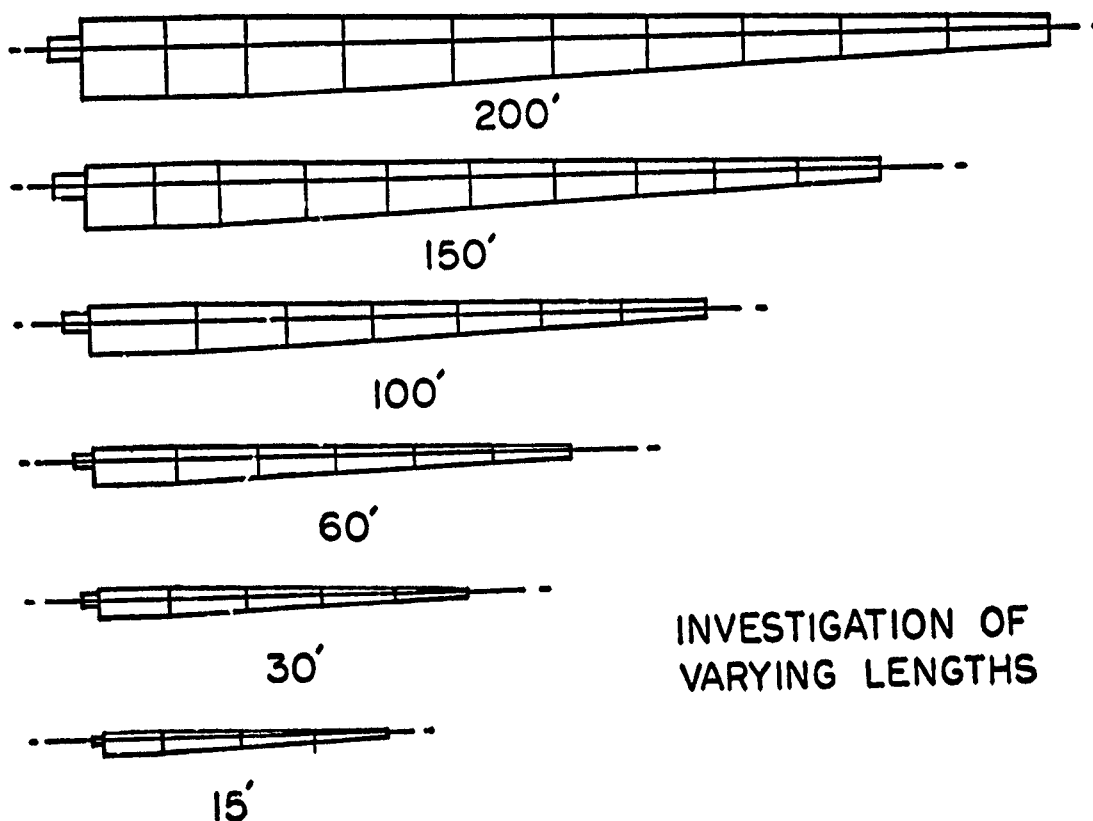


LEADING EDGES AND TIP  
TO SPAR ASSEMBLY

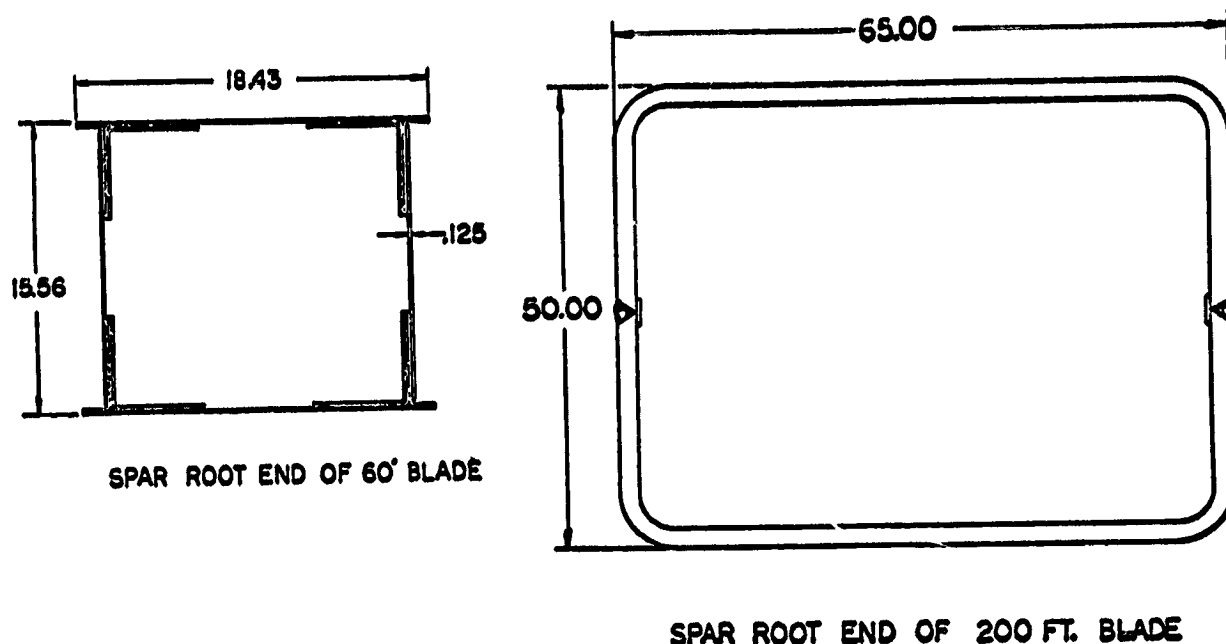


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A study to determine whether the basic concept of the design could be utilized through the entire range of blade sizes was made. The basic concept of a rectangular spar inside the aerodynamic surface carrying the principal loads with parasitic aerodynamic elements directing the air loads into the spar can be applied to the entire range of blades. The illustration below shows the blades that were reviewed in this study. Using the present configuration, with a high aspect ratio blade, we would use a stainless steel spar from the 60-foot size blade down to the smaller sizes. The advantage of the stainless steel spar is the ability to taper and spot weld the assemblies together at low cost and with good corrosion resistance for the thinner gage materials needed on the smaller blades. From the 60-foot blade on up, we would use a high strength, low alloy carbon steel for the spar. The reason for this is that the gage of the materials will be out of the range of those producible in stainless steels. Thicker gage cryogenic stainless steel material might be used, but we do not think this would be economically feasible in the larger size.



The illustration below shows the basic spar configuration for the 60-foot blade. This is constructed of 301 1/4 hard .125 thick stainless steel. Also shown is the general configuration of a spar of 200 ft length. It was basically the same design concept used for a 150-foot blade.

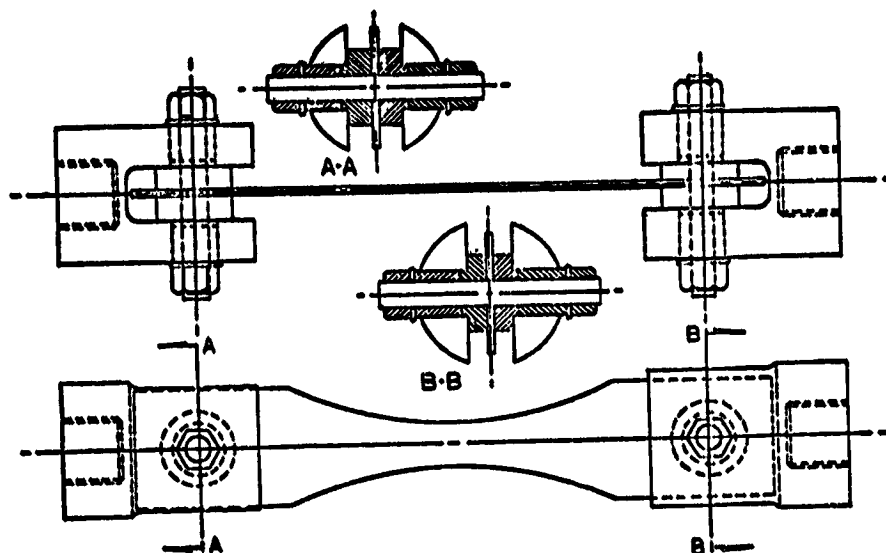


Our first cursory judgements are that it may be more practical to produce, at a lower cost, a multiplicity of smaller blades rather than a low quantity of larger blades for the same power output. Since the blade is only a small percentage of the total system, this conclusion may not hold when the whole system is considered.

Larger blades enter into an area of manufacturing which is beyond the present state of the art in many areas. To provide a good, low cost design will require considerable investigation. In the area of transportation, a blade up to 85 feet in length can be shipped in one piece without major difficulty. Above that size, the blades would have to be shipped in multiple pieces. This, of course, increases the problems of design of the blade, inasmuch as this would require spar joints outboard in the blade that would have to have the same degree of reliability as the root fitting. This can add considerable weight and cost but can be done. We are doing further investigation into the effects of varying lengths on design and their relative cost and weight.

### FATIGUE STRENGTH QUALIFICATION PROGRAM

In this section, we present a summary of the fatigue test program and the structural analysis. It covers the testing and the development of the allowable stresses used in the design. Summarized are the structural properties of the blade design. Testing of the fiberglass structures are discussed. The fatigue test program conclusions and the final blade design configuration were presented to NASA-Lewis on October 20, 1980. The illustration shows the configuration developed for the fatigue testing program. Considerable development was required to be able to perform satisfactory fatigue tests on the large full scale test specimens.

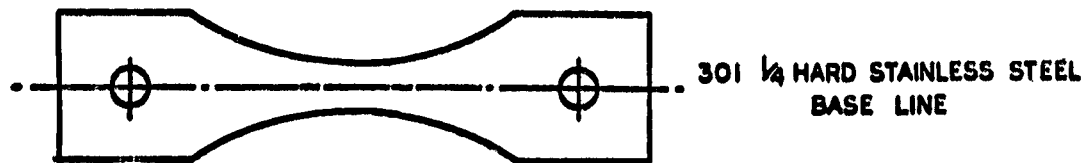


Parallel with the NASA full scale test element program, The Budd Company has conducted an in-house fatigue test program to obtain long term fatigue data on 301 stainless steel and the effects of joining techniques as related to long term fatigue. See the following series of illustrations and tables for the test results. We have used data from this program to supplement the full scale testing conducted under the NASA contract.

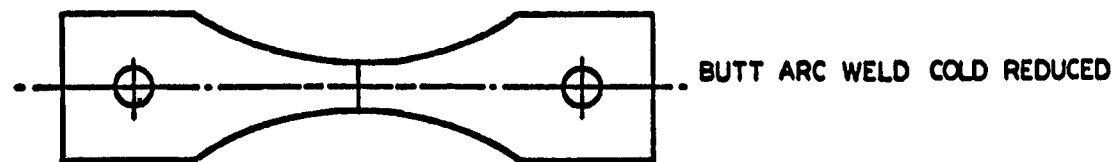
The 301 test series has been used to obtain base metal properties. All tests were run to 10 million cycles or more in tension-tension fatigue at +0.1 R value. Data presented are the minimum values without failures and have been adjusted to the blade design level of -0.5 R value using Goodman diagrams.

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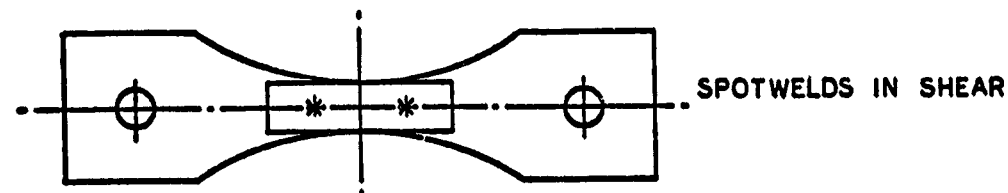
# BASE LINE TEST RESULTS



DATA  $\pm 49000$  P.S.I. CYCLIC STRESS  $-5$  R VALUE



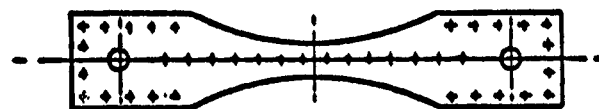
DATA  $\pm 24000$  P.S.I. CYCLIC STRESS  $-5$  R VALUE



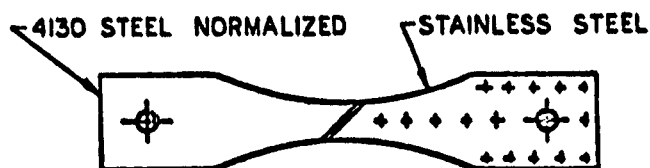
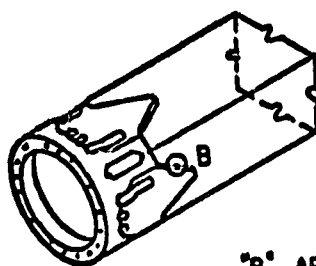
DATA  $\pm 562.5$  LBS CYCLIC LOAD PER  
WELD. SINGLE SHEAR.

## FULL SCALE CONFIGURATION TEST RESULTS

MULTIPLE LAYERS OF 301 STAINLESS STEEL  
SPOT WELDED TOGETHER



DATA  $\pm 21000$  P.S.I. CYCLIC STRESS  $-5$  R VALUE



"B" AREA REPRESENTED BY TEST SPECIMEN  
DATA  $\pm 16000$  P.S.I. CYCLIC STRESS  $-5$  R VALUE



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TEST PROGRAM CONCLUSIONS  
OF 301 1/4 HARD STAINLESS STEEL AND 4130 STEEL  
SUMMARY OF TEST LEVELS AT 10 MILLION OR MORE LOAD CYCLES  
ADJUSTED FOR "R" VALUE OF -.5

TEST	TEST VALUE	DESIGN ALLOWABLE (80% OF TEST VALUE)
		SHOWN IN CYCLIC STRESS
BASE METAL (301 1/4 H STAINLESS STEEL)	+ 49,000 PSI	+ 39,200 PSI
BASE METAL (BUTT ARC WELDED & COLD WORKED)	+ 24,000 PSI	+ 19,200 PSI
BASE LINE SPARE - SPOT WELDED	+ 21,000 PSI	+ 16,800 PSI
MAX SHEAR LOADS IN SPOT WELDS (R = +.1)	+ 562.5 (CYCLIC LOAD PER WELD)	+ 450 (CYCLIC LOAD PER WELD)
ROOT END ATTACHMENT - ARC WELDED	+ 16,000 PSI	+ 12,800 PSI
4130 CHROME MOLY STEEL	+ 38,000 PSI (CHART VALUE)	+ 30,400 PSI

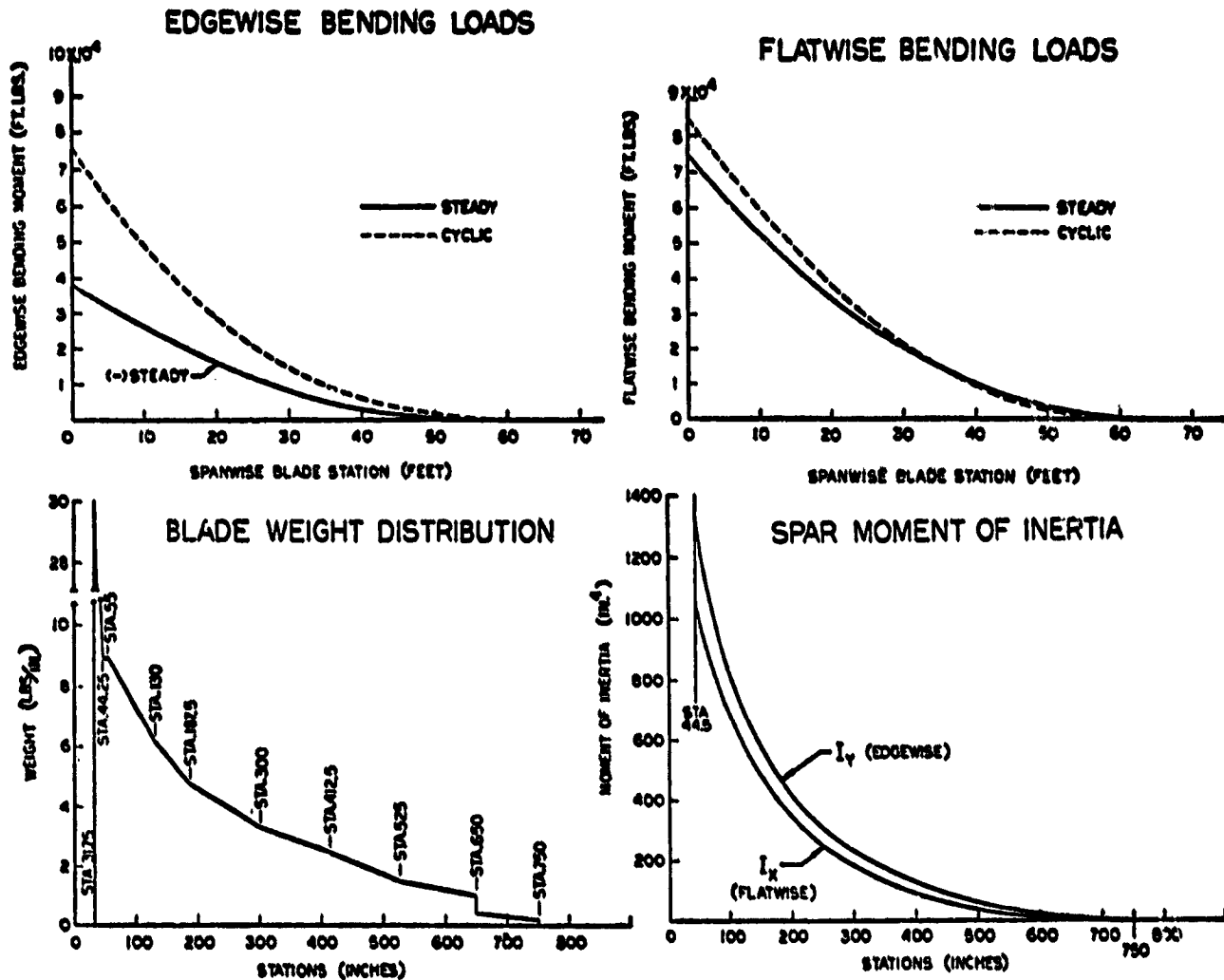
THESE ARE THE MAXIMUM ALLOWABLE STRESS LEVELS PERMITTED IN THE SPAR FOR FINAL DESIGN.

SUMMATION OF COMPUTED STRESSES IN THE SPAR

STA	WEB	CAP	MEAN PSI	CYCLIC PSI	MAX. PSI	MIN. PSI	R. MIN MAX	q (10 <sup>4</sup> in)
44.5	.125	.125	3340	11,000	14,340	-7660	-.53	103 ± 13
187.5	.125	.125	4814	15,914	20,728	-11,100	-.54	102 ± 18
300	.090	.125	5285	16,000	21,285	-10,713	-.50	104 ± 32
412.5	.090	.090	6753	14,300	21,053	-7547	-.36	85 ± 32
525	.060	.060	7790	12,383	20,173	-1593	-.23	73 ± 35
637.5	.060	.060	6278	6959	13,237	-681	-.05	74 ± 35

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The following series of charts describe the basic loads used for the design and the structural properties of the spar.

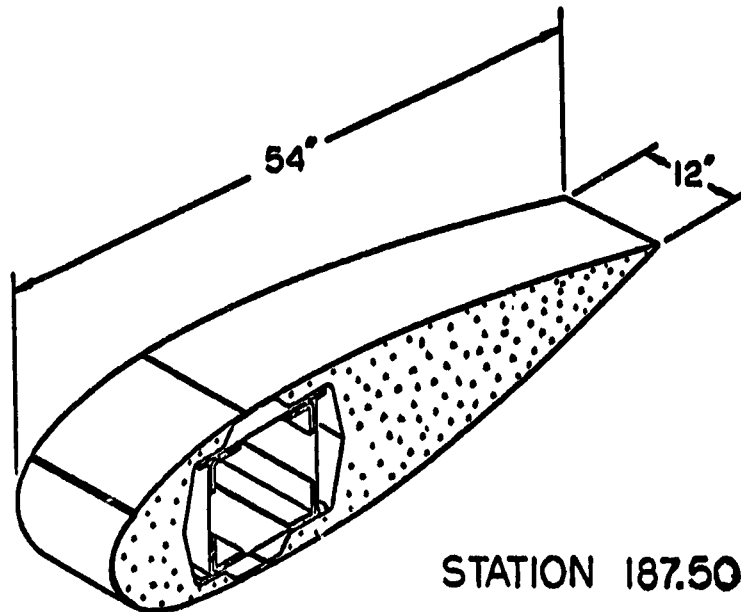


Computed blade assembly natural frequencies are 1.86 Hz in the flatwise direction and 2.15 Hz in the edgewise direction.

A test specimen was designed and manufactured to be used to determine manufacturing feasibility for the aerodynamic surfaces and to provide the fatigue test data for the system.

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The illustration lists the basic materials used for the aerodynamic surfaces and shows the test specimen used to evaluate the fatigue strength of the system. Weights were bonded over the aerodynamic surfaces equivalent to 1/2 the maximum aerodynamic load distribution. The specimen was then cycled  $\pm 1$  G to produce a 0 to 1 G load factor for the aerodynamic load and, as a function of the mass of the test specimen, a cyclic load of  $\pm 1$  G for the mass of the section. Additional tests were run as shown in the summary data on the next page. The results of the tests are excellent and indicate the design is conservative.



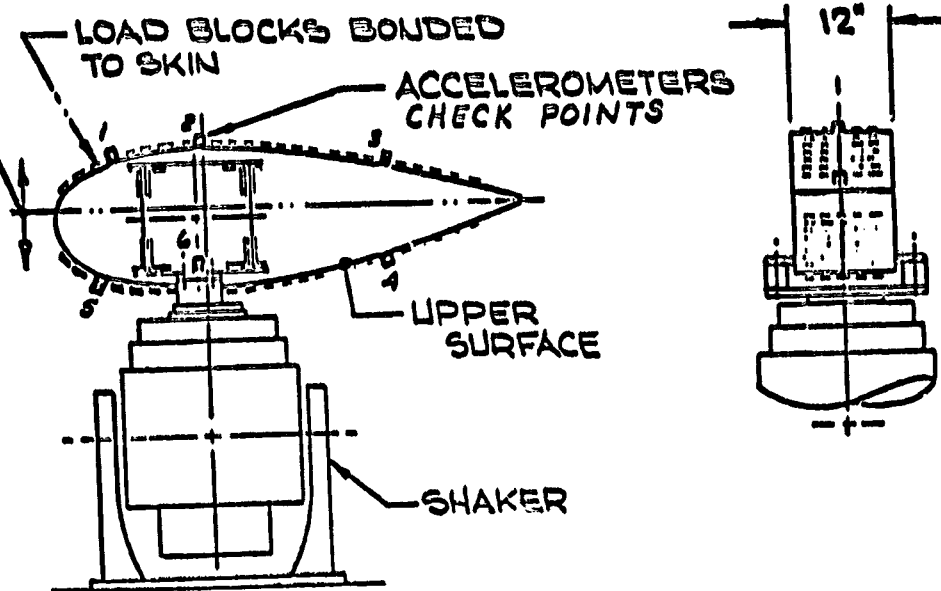
ONE FOOT WIDE BLADE SECTION  
USED FOR FATIGUE STRENGTH EVALUATION

MATERIALS OF AERODYNAMIC SURFACES

BASIC MATERIAL . . . . .	GLASS REINFORCED POLYESTER WITH 17% MIN. GLASS CONTENT
TRAILING EDGE SKINS . . . . .	.030 COMMERCIAL SHEET (AS ABOVE)
LEADING EDGE SKINS AND INNER CHANNELS . . . . .	COMMERCIAL LAY-UP (.060 TO .125)
FOAM (2-1/2 LB. DENSITY) . . . . .	RIGID URETHANE FOAM (MOBAY CHEMICAL CO. MB-237338A)
ADHESIVE . . . . .	3-M TWO COMPONENT ADHESIVE (EC-3549 B/A)

# SET UP FOR STA. 187.5 FATIGUE TEST

TO BE CYCLED  $\pm 1G$   
DYNAMIC LOAD WILL BE  
0 TO  $1G$  EQUIVALENT  
FOR THE DISTRIBUTED  
LOAD



## SUMMARY DATA TESTING OF FIBER GLASS AERODYNAMIC SURFACES DESIGN LOAD 50 LBS. PER SQ. FT. PROOF LOAD

### FATIGUE TEST

#### TEST #1

AERODYNAMIC LOAD EQUIVALENT FROM 0 TO DESIGN MAX.  
MASS LOAD EQUIVALENT FROM 0 TO 2 G  
TESTED AT RESONANCE (APPROX. 18 CYCLES PER SECOND)  
11,000,000 CYCLES (NO FAILURE)

#### TEST #2

AERODYNAMIC LOAD INCREASED TO  $-1$  TO  $+2$  DESIGN MAX.  
MASS LOAD INCREASED TO  $-2$  TO  $+4$  G 1,100,000 CYCLES  
(INDUCED MINOR FAILURE IN URETHANE BOND TO SPAR)

### STATIC TEST

- TEST 1 - LOADED TO 175 LBS. PER SQ. FT. (NO FAILURE)  
(CONTINUED  
NO REPAIR)  
TEST 1 - 24 HR. CREEP TEST AT 175 LBS. SQ. FT. (NO CREEP)  
(CONTINUED)

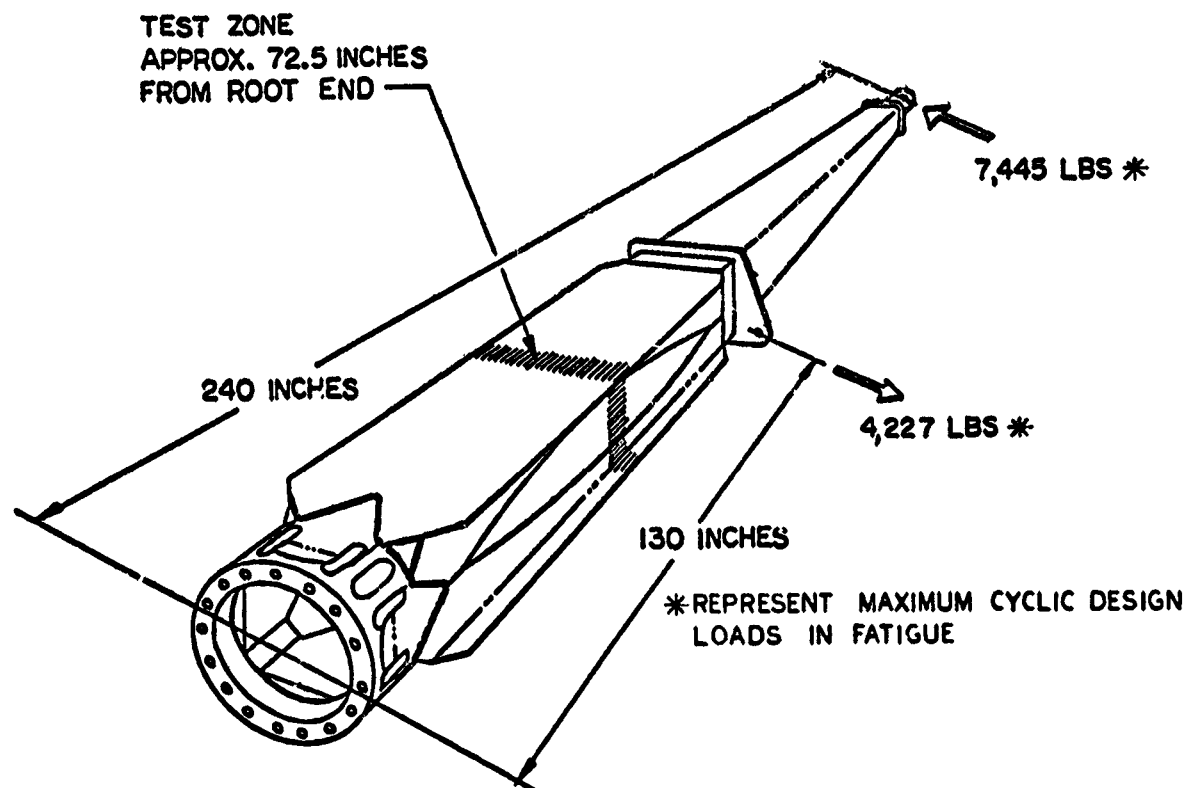
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### ROOT END TEST BEAM

To provide confirmation of the spar design, a full scale root end test section has been manufactured. This specimen was designed to apply the design load to the root end attachment fitting and at a zone approximately 6 ft from the root end to provide the maximum bending stresses in the spar determined by the analysis.

Shown in the illustration is the design of the root end beam. Analysis has shown that one way to accomplish a representative test is to apply opposing loads. This permits us to obtain a balance of the maximum cyclic stress on the spar and the maximum shear load on the assembly (top and bottom assemblies to side assemblies) spot welds. At the same time, the maximum moment and stresses are produced at the root end attachment. The loads described induce the maximum stresses used in the analysis. These are not the actual test loads. Testing levels will be adjusted to match NASA operating experience.

### ROOT END TEST BEAM



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COST STUDY 125 FT ROTOR

A comprehensive cost and weight analysis of the blade design has been made. The design was processed in detail and we have costed the blade as a function of the individual processes for each part and assembly.

The table shows the cost and weights of the blade and major sub-systems based on 100 units per year. The final blade design weighs less than 2,500 lbs.

COST ANALYSIS  
BASED ON 100 BLADES ANNUALLY

PART.NO.	DESCRIPTION	QTY	WEIGHT	MAT'L	LABOR	COST	TOOL COST
0510-100101	Spar Assembly	1	1635.7	2442	2904	5346	441,300
104	Trailing Edge Assy	1	86.4	222	176	398	54,500
105	" " "	1	66.6	173	172	345	50,800
106	" " "	1	95.1	135	150	285	45,300
107	" " "	1	45.3	114	141	255	40,300
108	" " "	1	33.4	84	128	212	36,000
121	Leading Edge Assy	1	73.6	287	86	373	41,000
122	" " "	1	52.7	253	86	339	40,000
123	" " "	1	40.9	170	75	245	34,600
124	" " "	1	30.9	138	66	204	30,500
125	" " "	1	21.5	107	60	167	27,800
126	Fiberglass Tip Assy	1	43.8	110	146	256	45,400
145	Joint Seal	5	12	10	-	10	-
146	Holding Brkt Boot	2	2	4	-	4	1,000
147	Upper Root Fitting Cover	1	7	24	5	53	5,200
148	Lower Root Fitting Cover	1	7	24	5	53	5,200
150	Spar Root Fitting Assy	1	1019.7	15	275	290	36,000
200	Root Fitting	1	100	169	396	565	66,000
	Adhesive	A/R	72.1	66	-	66	-
100	Blade Assy	1	-	53	704	757	219,700
TOTAL			2466	4600	5570	10170	1,215,000

Based on the guideline chart from NASA, we meet the cost criteria of the program. The cost estimate indicates a probably cost of approximately \$13,150 per blade which is considerably below the maximum allowable. See the chart and cost summary on the following page.

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The chart below was supplied by NASA to provide guidelines for the cost envelope versus weight for any blade design.

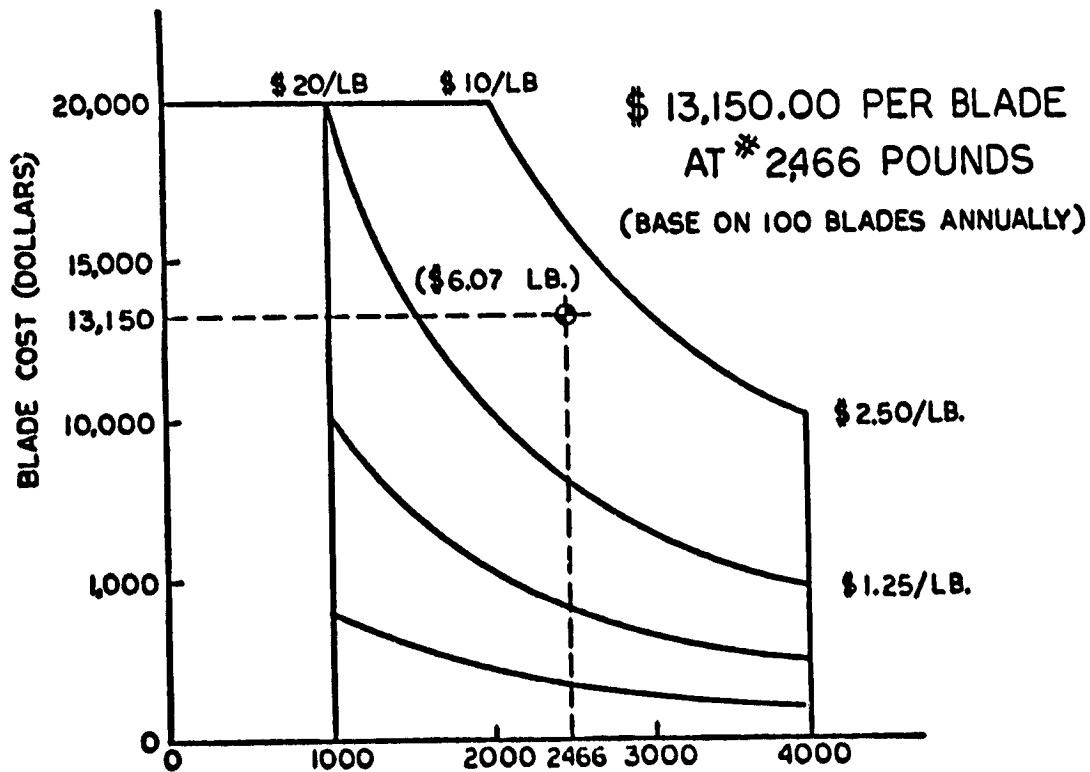
ESTIMATED COST SUMMARY  
BASED ON 100 BLADES ANNUALLY

TOOL COST

Tools 1,215,000  
Based on Production of 100  
Blades Annually  
Tool Cost 1,250 Per Blade  
(Tools Prorated on  
10 Years Production)

COST SUMMARY

Material	4,600
Labor	5,570
Tools	1,215
Total	11,385
5% G&A	570
Total Cost	11,955
10% Profit	1,195
Cost & Profit	<u>13,150</u> Per Blade



BLADE WEIGHT (LBS.)  
COST VERSUS WEIGHT DIAGRAM  
(COST CURVES FROM BASIC NASA DATA)

## CONCLUSION

The Budd Company completed Phase I of the contract. The Phase II program (Building of a Flight Set of Blades) is on hold pending future decisions on the need for blades for 125 ft diameter rotor systems and the funding for such systems. The trend of the wind energy program to build larger systems in the 300 ft rotor size requires further design study. We are very encouraged with the overall design concept and its many advantages when applied to larger systems. The concept permits the use of more complex airfoil systems with minimum effects on costs. It permits modular construction of all elements of the blade system which significantly improves producibility when applied to high volume production. The Budd Company is presently working on designs for application to large rotor systems and is available as a supplier to build such systems.



QUESTIONS AND ANSWERS

W. S. Eggert

From: Anonymous

Q: How do you propose to provide corrosion protection for the carbon steel spar?

A: *The spar would be primed and painted inside and out prior to assembly. Also, the heavy gage material 1/2 inch to 1 inch thick will stabilize quickly if corrosion exists.*

From: P. J. Pekrul

Q: Is the Budd design cost-effective in regard to weight, for the larger 200 ft blade length?

A: *This is the subject of a further detailed study, but early predictions indicate that a low carbon steel spar should be more cost-effective in the larger size.*

# THE DEVELOPMENT AND MANUFACTURE OF WOOD COMPOSITE-WIND TURBINE ROTORS

M. D. Zuteck  
Gougeon Brothers, Inc.  
706 Martin St.  
Bay City, MI 48706

This paper considers the physical properties, operational experience, and construction methods of the wood/epoxy composite MOD OA wind turbine blades. Blades of this type have now accumulated over 10,000 hours of successful operation at the Kahuku, Hawaii and Block Island, Rhode Island test sites. That body of experience is summarized and related to the structural concepts and design drivers which motivated the original design and choice of interior layout. Actual manufacturing experience and associated low first unit costs for these blades, as well as projections for high production rates, are presented. Application of these construction techniques to a wide range of other blade sizes is also considered.

## THE WOOD/EPOXY MOD OA WIND TURBINE BLADES

The MOD OA blades fabricated by Gougeon Brothers, Inc. of Bay City, Michigan are the largest blades built to date using laminated wood/epoxy composite as the primary blade structural material. They are also the most thoroughly tested, both in the laboratory and in the field, and will therefore be the primary topic of this paper.

The laboratory testing includes both component level tests of individual root end attachment studs and complete unit testing employing inner blade samples of 20 foot length. These tests supported the early design goals established for the wood/epoxy composite blades, and are reported in detail in another paper in these proceedings [1].

The wood composite MOD OA blades have also accumulated over 10,000 hours of operation while synchronized to a utility grid in normal power producing mode (called sync time), with over 6000 hours at the Kahuku Hills, Hawaii site, and another 4000 hours at the Block Island, Rhode Island site. Since the Kahuku machine is by far the leader in total power output, and because its blades have been through a few interesting experiences, the blades of the Kahuku machine will be the primary focus as regards operating experience. For a technical and quantitative review of in-field performance and load data, the reader can consult another paper in these proceedings which covers that topic in depth [2].

## MOD OA Blade Design Drivers and Concepts

This section will outline the basic blade design features, and the concepts and design drivers which lead to the selected configuration. The MOD OA design was heavily influenced by the requirement to produce a relatively stiff and lightweight blade with a chordwise center of gravity which was as far forward as practical. This led to a

configuration with a rather thick laminated Douglas fir "D" spar which makes up roughly the forward 1/3 of the airfoil. The walls of this "D" spar are about 15% of the local airfoil thickness, and the nose laminate thickness is reduced by step tapering the 1.6 mm (1/16") veneer in order to maintain the desired proportions all the way out the blade. The "D" is completed by a 6.35 mm (1/4") birch plywood shear web. The aft 2/3 of the airfoil is composed of a panel with 19 mm (3/4") paper honeycomb core and 3.2 mm (1/8") birch plywood skins in order to minimize weight in the tail while still providing adequate panel strength and stiffness. See Figure 1 for a typical section layout of this type. For the tip, outboard of radial station 15.24 m (600"), the inner ply has been deleted and a solid honeycomb core used in order to provide maximum strength and shape rigidity for this outer portion of the blade where maximum airloads and energy capture occur. The transition from tail panels to solid core tail is shown in the interior layout drawing, Figure 2.

The tail panels also feature a series of 19 mm (3/4") thick fir stringers which replace the honeycomb core along the panel forward edge. These stringers serve a dual purpose. They are an edge closure and bonding block for the tail panel itself, and also strengthen and stiffen the blade in flatwise bending. To serve this latter purpose and provide the desired margin against the design driving emergency shutdown loads, these stringers reach a total width of 200 mm (8") in the inner blade and then taper away as they proceed toward the tip. There is also a stringer at the aft edge of the tail panel which closes that panel edge and serves as the trailing edge mating and bonding surface after it is trimmed.

Inboard of radial station 3.81 m (150") there is a transition region to the standard 24 bolt 473 mm (18.625") diameter MOD OA bolt circle. This involves a gradual buildup of the shear web from the 6.35 mm (1/4") birch ply used for the outer blade to over 100 mm (4") of laminated fir needed for load take-off at the root. Corner blocks of laminated fir are used to fill the corner where the nose lamination and shear web buildup meet at the root, so that all of the studs in the bolt circle will be properly embedded in fir laminate. The transition region also includes laminated fir diagonal braces built into the tail panels which serve to collect the edgewise loads from the tail panels and direct them to the root buildup. The tail panels are cut away aft of these internal diagonal braces in order to save labor and associated costs, by providing easy installation of the required diagonal rib which then also serves as the transom piece/tail closure.

Load take-off at the root is accomplished by means of 24 bonded in place steel studs of 15" embedded length and tapered design. The laminate at the root is increased to 124 mm (4.875") of Douglas fir/epoxy in order to better transfer load into these studs. Originally intended to bolt directly to the hub spindle at station .813 m (32"), the studs now mate a steel spool piece at radial station 1.27 m (50") due to doubts that the original MOD OA spindles were stiff enough to allow the stud attachment method to work properly. To compensate the additional .457 m length due to the spool piece, .457 m was simply trimmed from the tip for the first set of blades. That first set was

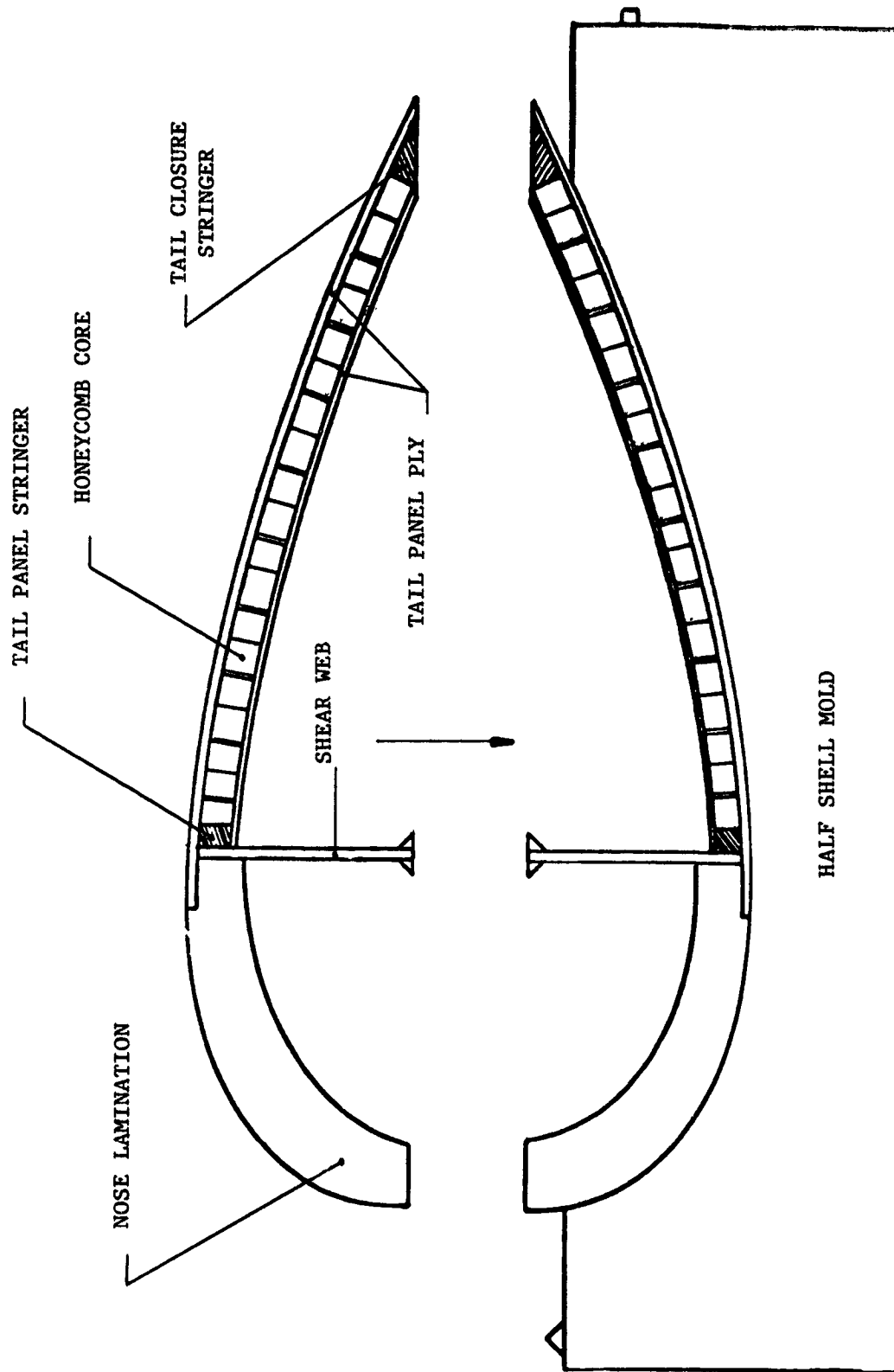


FIGURE 1  
ILLUSTRATION OF TYPICAL BLADE CROSS-SECTION

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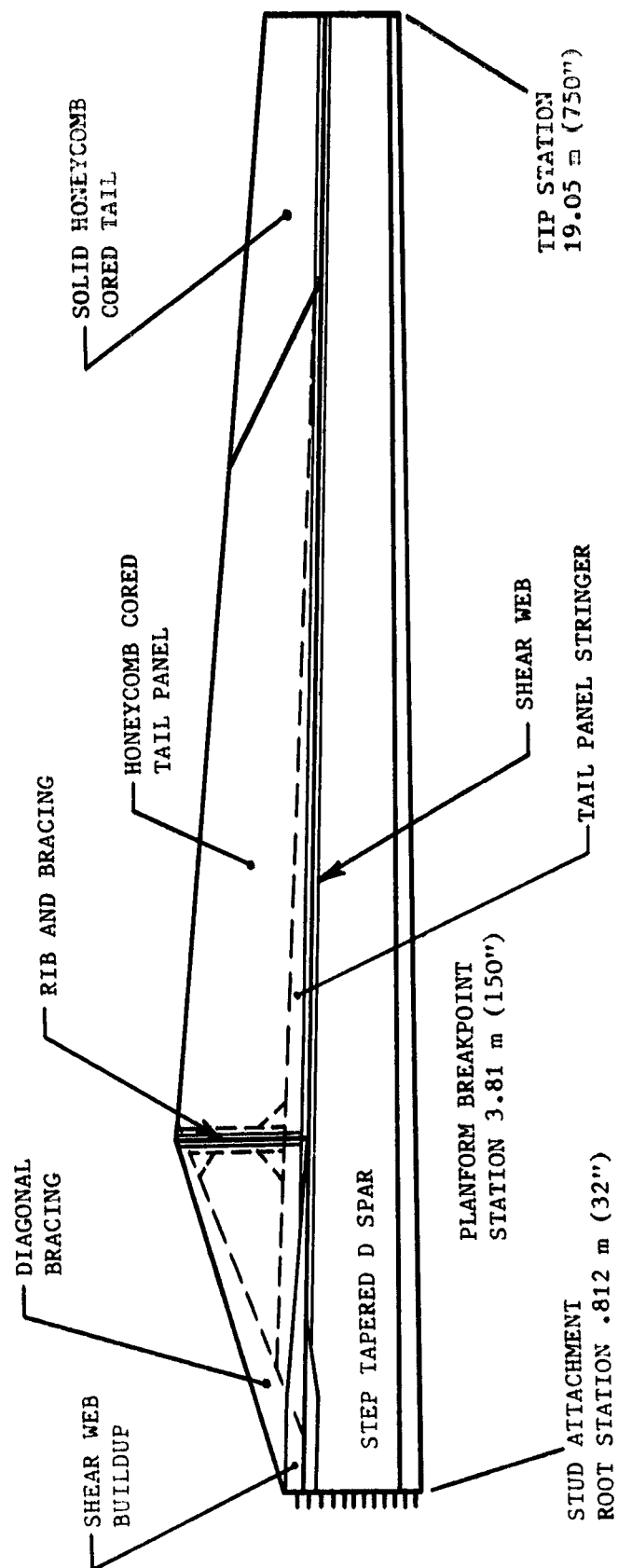


FIGURE 2  
INTERIOR LAYOUT DRAWING

christened the Dave Peery blades in honor of a gentleman who provided help, guidance, and encouragement in the early work on wood/epoxy blade design. Later blades were likewise trimmed by .457 m in length, but were also reduced by roughly 3 mm (1/8") in "D" spar thickness to compensate moving the blade outboard. Presumably a redesigned and suitably stiffened spindle would allow elimination of the heavy steel spool piece and a return to the full blade length and D spar thickness. That would save considerable weight, since the spool piece has a mass of about 180 kg (400 lbs weight), and would also reduce overall costs. Aside from that, however, the overall mechanical and aerodynamic performance of the blades would change very little from what it is today.

### External Blade Geometry

The wood/epoxy MOD OA blades employ the same 230xx airfoil section as the original aluminum blades. This choice was governed primarily by the desire to hold section shape constant so that this would not be a variable factor in comparisons between different blade types. As it turned out, the loads and blade deflections experienced during high feather rate emergency shutdown turned out to be the major design driver for the geometry and thickness of the whole blade, except for the root design, which was driven by fatigue. Those loads and deflections could have been materially reduced by the choice of an airfoil section which stalls sooner when at negative attack angles, which in turn would have allowed a lighter blade or smaller t/c ratios, but at the cost of making performance comparisons more uncertain. Since research results are very important to the MOD OA program, the 230xx series airfoils were retained in spite of the resulting structural demands, and the entire geometry choice must be viewed with this in mind.

The blade planform varies linearly from 570 mm (22.5") at the root plane to 1585 mm (62.4") at the trailing edge breakpoint to 610 mm (24") at the tip. The leading edge is a straight line from tip to root except for a small pullback near the root which was introduced to smooth the root transition geometry. The trailing edge is a straight line between the trailing edge breakpoint and the tip, and provides  $4.8^\circ$  of twist over outer blade. The straight trailing edge was partly a manufacturing simplification, but was also found to provide a good match to the chosen planform when viewed from the standpoint of achieving good net energy capture over the whole band from cut-in to design windspeeds, as opposed to maximizing energy capture right at the design windspeed. The blade thickness varies from 566 mm (22.3") at the root, to 498 mm (19.6") at the trailing edge breakpoint ( $t/c = 31/4\%$ ), and linearly to 46 mm (1.80") at the tip ( $t/c = 7.5\%$ ). This rather thin tip was chosen to help promote early stall in the emergency shutdown condition, although some drag reduction benefit in the power producing mode could also be argued to exist. Table 1 provides a more detailed tabulation of blade planform, twist, and thickness values.

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TABLE 1  
MOD OA BLADE EXTERNAL GEOMETRY DATA

STATION m (ins)	CHORD LENGTH m (ins)	MAX THICKNESS		THICKNESS/CHORD %	TWIST degrees
		mm	(ins)		
.813 (32)	.571 (22.5)	566	(22.3)	-	0
2.59 (102)	1.207 (47.5)	531	(20.9)	-	0
3.81 (150)	1.585 (62.4)	503	(19.8)	31.7	0
7.62 (300)	1.341 (52.8)	389	(15.3)	29.0	0.6
10.16 (400)	1.179 (46.4)	312	(12.3)	26.5	1.0
12.70 (500)	1.016 (40.0)	236	(9.3)	23.3	1.7
15.24 (600)	.853 (33.6)	160	(6.3)	18.7	2.6
17.78 (700)	.691 (27.2)	84	(3.3)	12.1	3.9
19.05 (750)	.610 (24.0)	46	(1.8)	7.5	4.8

### Manufacturing Methods

After considering several alternatives, the Gougeon Brothers organization settled upon the use of vacuum molding with female half shell molds as the most promising technique for economical volume production of laminated wood/epoxy blades. This method insures uniform clamping pressure for both the nose lamination and the tail panels during resin cure, and also conforming the wood components to the desired shape.

In practice, the molds are first coated with release agent followed by epoxy and glass cloth. This glass cloth and epoxy forms a tough, damage and weather resistant outer skin. It also serves to help tie together the nose laminate grain, which runs in the spanwise direction. Next a layer of aluminum screen is added, which serves to provide lightning protection by enclosing the main blade structure within a conductive shell. This screen covers most of the blade surface, except for a region at the tail near the breakpoint. The screen is connected to a grounding bar at the blade root so that the current can be collected and taken to ground. Next into the mold are the plywood and honeycomb which make up the tail panel, the tail panel stringers, and a ply sheath made of two layers of 1.6 mm (1/16") ply which covers and further strengthens the exterior of the "D" area. Under current procedures, these components are then vacuum bagged in place and allowed to cure. The half shear web and the root buildup at the root is added next. The last major molding operation is the placement and bagging of the nose veneers. Each half blade is then trimmed via a special rail mounted horizontal bandsaw, and the fit of the upper and lower halves is carefully checked before they are bonded into a single unit.

The root of the blade is then trimmed to the proper plane and capped with birch plywood. The mating surfaces for the transom piece are also trimmed to size and the transom piece is bonded in place at this time.

Installation of the root attachment studs involves precise drilling of the 24 oversize step tapered stud holes and complete wetting out of the exposed laminate inside the holes. The studs are all attached to a single precisely machined plate so that relative stud positions can be assured to a high degree of accuracy. The holes are then filled with thickened epoxy and the stud assembly is accurately positioned in place and allowed to cure.

Final blade finishing operations include items such as installation of the blade tip cap and tip drain system, cleanup of excess resin along the blade half joint line, and exterior painting and addition of station marks and blade identification.

### Production Results and Experience

The first set of MOD OA blades produced had a mass of 1183 kg (2603 lbs) each without the spool piece, with the center of gravity at 5.702 m (224.5") relative to the blade root plane. This was somewhat



heavier than expected, and was primarily due to a larger than planned use of resin, particularly for filling the volume occupied by the lightning protection screen. A change in procedures and more restrained use of resin, along with the already mentioned slight reduction in "D" spar wall thickness allowed a reduction of blade mass to 1002 kg (2205 lbs) for last set produced, which includes 4 kg (9 lbs) in one blade and 6 kg (14 lbs) in the other to match weights and centers of gravity. The center of gravity moved inboard by 10 cm (4") to 5.602 m (220.4"), again measured from the blade root plane. The weight of this last set of blades is felt to be about the practical minimum for the present design. Significant further weight reductions would require a change in airfoil section and an adjustment in the interior proportions.

A breakdown of the major blade material weights and costs is presented in Table 2 in order to provide a better perspective on the actual makeup of the blade. The table is for a full length blade with full thickness "D" spar and consequently shows a higher total blade weight than the actual production blades.

The single step lamination of the "D" spar, which involves about 500 kg (1100 lbs) of 1.6 mm (1/16") thick fir veneer (800 m<sup>2</sup> (8700 ft<sup>2</sup>)) is the largest single step vacuum lamination of veneer known. In order to accomplish this within the roughly 1 hour time limit required for the epoxy resin system used, a special veneer coating machine is used to quickly apply a precise quantity of resin to both sides of the veneer. In the early feasibility studies for the wood/epoxy blades, it was not known if it would be at all possible to move the required mass and area of veneer within the time required, but this has in fact turned out to be both practical and efficient. The upper limit has not yet been reached.

#### OPERATIONAL EXPERIENCE

The first set of wood/epoxy MOD OA blades were sent to the Kahuku, Hawaii site. When they were inspected upon arrival, it was found that both trailing edges were split apart for many feet and that one of the transom pieces was also split away along its edge. Since this first set of blades had not been purposely vented, it was quickly suspected that this damage could be due to a pressure buildup problem. The Bay City plant of Gougeon Brothers is about 200 m (600 ft) above sea level, and shipment to Hawaii was via ship at sea level, and that difference could not account for the splitting observed. However, when the overland route of the truck from Bay City to Los Angeles was traced, it was found that a 2100 m (7000 ft) mountain pass had to be negotiated along the way. That would result in an interior pressure of more than 1000 N/m<sup>2</sup> (3 psi), which was well in excess of the capability of the tail closure joint, which had not been designed for pressure vessel service. The failure was inevitable.

Meade Gougeon, chairman of Gougeon Brothers, Inc. immediately flew to Hawaii to personally lead the in-field repair effort. In a matter of a few days, the blades were repaired right at the wind site using normal WEST SYSTEM products and repair techniques. (Total expenditure

TABLE 2  
MATERIAL COST AND WEIGHT BREAKDOWN

Item	# Wt in Blade	Total Amt Needed	Unit Price	Cost Mid 1979 \$
Douglas fir veneer 1.6 mm thick (1/16")	514 kg (1131) lbs	808 m <sup>2</sup> (8700 ft <sup>2</sup> )	\$1.61/m <sup>2</sup> (15¢/ft <sup>2</sup> )	1305
24 steel studs	55 (120)	24	\$40 each	960
Epoxy	202 (445)	223 kg (490#)	\$3.00/kg	662
Birch aircraft plywood 3.2 mm thick (1/8")	121 (266)	65 m <sup>2</sup> 700 ft <sup>2</sup>	\$6.90/m <sup>2</sup> \$64¢/ft <sup>2</sup>	448
Birch aircraft plywood 1.6 mm thick (1/16")	28.5 (63)	30.5 m <sup>2</sup> 330 ft <sup>2</sup>	\$6.00/m <sup>2</sup> (56¢ ft <sup>2</sup> )	185
Lightning protection and ice detector	4.5 (10)			125
Miscellaneous Paint, nose strip, etc.	7.3 (16)			100
Douglas fir sawn stock	64.5 (142)	91 bd ft	74¢/bd ft	67
Fiberglass, 10-ounce 60" wide	13.6 (30)	32 m 35 yds	1.64/m (1.50/yd)	53
Birch aircraft plywood 6.4 mm thick (1/4")	24 (53)	6.4 m <sup>2</sup> (69 ft <sup>2</sup> )	8.00/m (75¢/ft <sup>2</sup> )	52
Vertical honeycomb	12.7 28	33.5 m <sup>2</sup> (360 ft <sup>2</sup> )	1.45/m (13.3¢/ft <sup>2</sup> )	48
TOTAL	1047 2304	-----	-----	4005

of man hours and materials was approximately 24 hours and \$100.) Since the time of that in-field repair, those blades have seen over 6000 hours of sync time with no indication whatever of distress in the area of the repairs. Several interesting observations can be made based on this experience. It has demonstrated that the structural integrity of these laminated blades is such that they are perfectly airtight structures - there are no significant breaks in the structure proper or its many bond lines. Pressure equalization for shipping or for a possible hurricane environment must be explicitly provided if desired. All subsequent blades are now vented at the tip for moisture removal as well as pressure equalization. It has also shown that the wood/epoxy construction system is suited to rapid and relatively simple in-field repair, and that such repairs to date have not had an adverse effect on service life. This is not a surprising result to those familiar with this construction system, as it is known that the resin system is several times stronger than the cross grain strength of the wood which it bonds; however, those unfamiliar with the system may want to consider the implication of this as it relates to the ease of in-field repairs and overall maintenance costs.

#### Emergency Shutdown

Early in the operation of the Kahuku MOD OA machine, a true overspeed emergency shutdown was encountered. This condition was the design driver for both the flatwise strength and stiffness of the wood/epoxy blade structure. It constitutes the most severe one time load test for which the blade design was qualified. The test result was negative: no visible damage was observed, and the blades still fly.

#### Periodic Inspections

The blades have been subjected to periodic inspection of a detailed nature by hoisting an inspector right up to the blade for close, hands on inspection. A summary of those inspection observations is given in the wind turbine project report prepared by Hawaiian Electric [3]:

"The most significant improvement affecting reliability and availability of Makani Huila has been the wood-resin composite blade. The three other machines have required major blade repair or replacement within the first 2000 hours of synchronous operation. Makani Huila has passed that milestone with no sign of blade deterioration.

The composite blades have proven particularly suited to Hawaii's moderate climate. The salt laden ocean breezes have had no apparent negative effect on the blades. The resin protected blades are impervious to water and unattractive to termites. The natural resiliency of the wood has eliminated premature fatigue failure. The resin glue has eliminated the rivet problems that have plagued the aluminum blades of previous machines. The blades are performing admirably.

The first scheduled 1000-hour inspection (actually performed at 640 sync. hours) showed only minor separation near an unloaded section of the blade root. Some paint touch-up was done. The 2000-hour inspection revealed no significant changes in blade condition. If the separations noticed during the first inspection have propagated at all, the change has been too small to warrant corrective action. No special operational precautions have resulted from the inspections. The blades are in excellent condition."

It should be noted that the aluminum MOD OA blades were designed and built using standard accepted aircraft design and fabrication techniques. But they were the trailblazers, and could not draw on previous experience regarding the actual severity of the wind turbine blade fatigue environment. Viewed in that light, their performance was not unreasonable, and a lot of knowledge was gained. It is encouraging that the emerging wood/epoxy technology was able to draw on that experience base and provide a working blade at comparable blade weight (without spool piece).

#### Power Output

The Hawaiian MOD OA machine at Kahuku Hills was formally dedicated on July 3, 1980. By July 16, 1981, just over 1 year later it had achieved over 6000 hours of sync time, and had delivered more total power to the utility grid than any of the other MOD OA machines, including the Clayton, New Mexico machine, which began operation in late November of 1977. The Kahuku machine has averaged nearly 100 kw over this first year which is a power factor of about .5, even though some down time for inspections and minor repairs is also included. Taken against actual hours on line, the machine has averaged about 150 kw. This is in large measure a direct result of the excellent wind regime at Kahuku Hills, and is also a tribute to the energy and dedication of the wind power team of Hawaiian Electric. However, the consistent and troublefree performance of the wood/epoxy blades has also been an important element in that success. For a more detailed report of the operating experience of the MOD OA machines from the standpoint of quantity and quality of power delivered, the reader is directed to another of the papers in this proceedings [4].

#### Long Term Durability - Fatigue

The MOD OA machines are oriented with the blades downwind of the tower. This causes each blade to experience a significant region of sharply depleted wind velocity once each revolution. The result of this can be seen in many ways. Most obvious is an audible low level thump as each blade passes behind the tower. This is due to the rapid unloading and restoration of the dynamic pressure distribution around the blade. This presents a significant fatigue environment to the blade structure, particularly near the tip where dynamic pressures are highest. In particular the honeycomb cored tail would be the part of the structure most susceptible to this pulsating pressure distribution. However, the design calculations

showed large margin against this fatigue mechanism, and so far experience has not shown any problem in that area.

The wind shadow effect also causes a transient vibration of the entire blade. The flatwise vibration damps out quickly due to aerodynamic damping but its effect is visible in the traces of flatwise root loads [2] and also is visible to the eye if carefully observed. The edgewise vibration is not visible to the eye. However, it is visible on the data traces [2], both as a 5 per rev, edgewise load variation at the root and as a fluctuation in generator power output.

The overall set of loads seen at the blade root constitute a real design challenge at the root stud load takeoff of the MOD OA blades for long term fatigue. It was in recognition of this fact that NASA performed extensive fatigue testing of both individual studs and entire inner blade sections. The performance of these specimens indicates that the blade root should be able to sustain the long term fatigue loading environment, but the design margin there is certainly not as large as it is elsewhere in the blade. It should be pointed out that significant advances in stud performance were made during early design and testing work, and that further advances in performance almost certainly still remain. Even at the present level of development, this wood to steel load takeoff method has been demonstrated to be reasonably efficient both for one time loads and for long term fatigue loads.

The primary wood/epoxy blade structure has large margin against fatigue both from the airloads which load the structure flatwise and the gravity moment which loads it edgewise. The fatigue margins are typically in excess of 100% throughout all of the major structural elements. For bonds and joints which act in crossgrain loading, margins on the order of 300% to 500% were typically provided largely because the low density of wood allowed generous bonding area and made such margins easy and practical to attain. If these margins in fatigue seem large, one must remember that it was the one time loads of overspeed emergency shutdown which drove much of the design of the current MOD OA blades, and that wood is a material with very good fatigue properties relative to its weight. One should consider that nature has spent millions of years in the serious business of competitive survival in order to develop good strong trees, which must stand repeated and highly variable loads from winds and other load sources, and it is therefore not too surprising to find that wood is an efficient structural material with very respectable fatigue properties. The current design acknowledges and benefits from those properties.

### Environmental

Nature determined long ago that its structures must be biodegradable and recycleable. It could not afford to have its forests cluttered up with indestructable fallen trees. Man is also beginning to realize the necessity of this approach. The ability of wood to decay is a positive necessity in the overall scheme of things, but has been an inconvenience and limitation in mankind's structural use

of wood. It is important to point out that this decay is not a simple function of the passage of time. Healthy trees can stand for centuries with no apparent loss of properties. Samples of wood entombed in the pyramids for thousands of years have been found to be as sound structurally as recently cut wood. Time alone has very little effect.

The decay process of wood requires an elevated moisture content and a supply of oxygen. There is no "dry" rot. The fiberglass/epoxy outer blade sheath provides not only a tough physical skin, but also an effective barrier to the passage of moisture and oxygen. All of the bond lines and lamination glue lines provide additional and redundant barriers. The net effect is to provide the wood with a moisture stable environment without free oxygen. Both of the requirements for decay are absent - the wood is more effectively isolated than either living trees (elevated moisture) or pyramid entombed (some free oxygen) wood. It can be pointed out that lightweight wood/epoxy boats protected with this technique have now survived over 12 years in the relatively severe marine environment with no evidence of degeneration. Thus there is no a priori reason to expect that suitable longevity would not be possible in the wind turbine environment. Only time and experience will finally give proof, but the prospects are good in view of our present knowledge.

#### THE FUTURE FOR WOOD/EPOXY WIND TURBINE BLADES

To date the wood/epoxy construction technique has been applied to the construction of blades as large as the 19 m (62.5 ft) MOD OA, and as small as 6.7 m (22 ft). By the time this is printed and distributed, blades of 3 m (10 ft) length will be in production. In the NASA/DOE sponsored MOD 5A effort, a wood/epoxy rotor was selected at the conceptual design level. That rotor would be 122 m (400 ft) in diameter, which is a single blade length of 61 m (200 ft). It therefore appears at this time that the wood/epoxy construction technique is a viable choice over the whole size range of power generating wind turbines. The primary advantages of the material which appear to suit it particularly well to the wind turbine blade application are several;

- 1) low basic material cost
- 2) relatively low resin use as a percent of overall weight
- 3) high per unit weight strength and stiffness
- 4) exceptionally high per unit weight fatigue capability
- 5) thick shells for simple, buckling resistant design
- 6) resin stronger than base material gives easy bonding and repair
- 7) high corrosion and weather resistance
- 8) smooth accurate airfoils
- 9) totally bonded monolithic structure

Overall, it appears that the basic technical capability of the laminated wood/epoxy material in the wind turbine blade application is reasonably well established, even though there are a number of areas

where further development and better experimental characterization would allow more efficient design.

The economics of blade production are also becoming reasonably well defined. It took about ten men and two months to build the molds and first pair of MOD OA blades. This does not include building the plug from which the molds were taken, and some long hours were admittedly involved, but this still gives a feel for the time and effort involved in pursuing this method of construction. Also bear in mind that this was a first time production run, with lots of first time bugs and problems to be worked out. Given all of the above, this overall performance seems a good argument that the basic technology must be reasonably efficient in terms of time and manpower. Using the present tooling as is (no tooling/setup costs), and including no costs associated with subsequent shipping and the like, a MOD OA blade can now be produced for about \$40,000. By setting up for a production run of 100 blades per year or more, and making a few blade design changes to improve costs and producibility, it is felt that the blade costs could be cut roughly in half. There are many avenues left to explore in the realm of cost effective production, but the initial results are encouraging. Aggressive work is in progress to improve the basic knowledge and techniques associated with the laminated wood/epoxy material, and it appears that this material now warrants serious consideration at all size levels of the modern electric power generating wind turbine.

### Acknowledgements

Special acknowledgement is in order to several members of the Gougeon Brothers organization for help in providing specific cost and manufacturing data, and for help in preparing the text and illustrations; to the wind energy staff of NASA Lewis Research Center for valuable loads and performance data; and to Dave Rodrigues of Hawaiian Electric for conversations and data relating to the actual physical condition of the blades in the service environment.

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3. Wind Turbine Project - Operation and Maintenance of a 200 kW Wind Turbine A. Fujinaka, G. Miyashita, D. Rodrigues
4. Operating Experience with Four 200 kW MOD 0A Wind Turbine Generators A. Birchenough, Saunders, Myland, Shaltons



QUESTIONS AND ANSWERS

M. Zuteck

From: A. Saunders

Q: Has there been any evaluation of the effect of hydraulic fluid on stud bonding?

A: *No, but a stud was tested in fatigue with mold release on the stud to totally compromise the bond. No significant loss of performance was observed. Presumably failure of bond due to corrosion or intrusion of a substance such as hydraulic fluid would be similarly benevolent.*

From: G. B. Ketley

Q: What cyclic and steady stress allowables do you assume for the basic wood laminate?

A: *The allowables for wood laminate are dependent upon the specimen moisture content and the specimen temperature, and decrease when either increase. These variables must be specified to pin down allowables. At standard conditions (68°F and 12% mc) for Douglas fir laminate, the basic allowables are about 7500 psi compressive, 15000 psi tensile. In fatigue relative to a 12500 psi modulus of rupture and for 10<sup>6</sup> cycles, the allowables are 36% for repeated loads and 27% for fully reversed. Grain runout, density of the veneer, and defects should also be accounted for in setting allowables.*

From: P. Henton

Q: Is balancing of the two blades a problem?

A: *It is easy to do via adding controlled amounts of thickened epoxy to the nose cavity, to balance both overall weight and cg location. As a perspective, on the last set of blades, 9 lbs was needed in one blade and 14 lbs was needed in the other. That is, less than 1% of the 2205 lb finish blade weight.*

## STRUCTURAL FATIGUE TEST RESULTS FOR LARGE WIND TURBINE BLADE SECTIONS

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## ABSTRACT

In order to provide quantitative information on the operating life capabilities of wind turbine rotor blade concepts for root-end load transfer, a series of cantilever beam fatigue tests was conducted. Fatigue tests were conducted on a laminated wood blade with bonded steel studs, a low-cost steel spar (utility pole) with a welded flange, a utility pole with additional root-end thickness provided by a swaged collar, fiberglass spars with both bonded and nonbonded fittings, and, finally, an aluminum blade with a bolted steel fitting (Lockheed Mod-0 blade).

Photographs, data, and conclusions for each of these tests are presented. In addition, the aluminum blade test results are compared to field failure information; these results provide evidence that the cantilever beam type of fatigue test is a satisfactory method for obtaining qualitative data on blade life expectancy and for identifying structurally underdesigned areas (hot spots).

## INTRODUCTION

NASA-Lewis Research Center is currently evaluating the operational performance of large wind turbines for the Department of Energy. The objective is to develop the technology base for large horizontal-axis wind turbines to produce electricity that is competitive with alternate energy sources.

One of the main components of wind turbines that requires technology development is the rotor. For large wind turbine systems, which have rotor diameters of from 125 to 300 feet, the rotor cost is generally in excess of 25% of the installed machine cost. In addition, the wind turbine rotor operates in a severe fatigue load environment, which may lead to high maintenance and/or replacement costs for blades with structural design deficiencies. Consequently, as part of the wind turbine program, a major effort is being expended on reducing rotor blade cost and qualifying the blades for a 30-year life.

One of the major areas of concern in the design of wind turbine generator (WTG) blades is the ability of the root end (the innermost section of the blade) to transfer the fatigue loads from the main spar section into the WTG hub. The root end is of particular concern because this is where bending moments reach their highest values; in many cases, this is also an area of transition between steel and some other material. Consequently, it is desirable to test new blade concepts in fatigue.

To accurately evaluate the design, testing would involve fabricating a full-scale root end section and subjecting that section to the load spectrum that would be experienced in the field. However, since the load spectrum occurs over a 30-year life and includes centrifugal, torsional, and bi-axial bending loads, all phased to one another, simulating the time phased load history is impractical. Testing to date has been done on the premise that loads other than the bending loads resulting from aerodynamic lift/drag and gravity forces produce negligible stresses and can thus be ignored. Further, the maximum flatwise and chordwise bending loads occur at approximately the same time and can be approximated (conservatively) as a single resultant moment. The load history would still involve as many as  $4 \times 10^8$  cycles at the simplified design operating loads. At a test rate of 10 Hz, in excess of 1-1/4 years of continuous round-the-clock testing would be required to accumulate the required number of cycles. Thus, the testing is further simplified by applying higher loads for a smaller number of cycles and over a shorter period of time.

The resulting simplified test program (typical) uses a full-scale root end section of a WTG blade mounted as a cantilever beam to a very stiff test stand. The root moment is achieved by applying a single shear force at the outer end of the blade test section. The magnitude of the shear force is adjusted to approximate the desired resultant moment at the inboard section of the blade. One or two million load cycles are then applied under each of a number of load conditions that are representative of predicted blade operating conditions. The test procedure has been used on a series of Mod-0A blade sections, which include: (1) a prototype laminated wood blade, Ref. 1; (2) a steel spar blade with wood ribs and cloth skin; (3) a steel spar blade as in (2) but with a reinforced spar root end; (4) the final design configuration for the laminated wood blade, Ref. 2; (5) a 1/2 scale fiberglass composite spar with both a bonded and unbonded root end fitting; and (6) a spare aluminum blade from the Mod-0 program. A brief description of each of the blade concepts and the results of the test program are included in this report.

#### DESCRIPTION OF FACILITY

The U.S. Army Applied Research and Technology Laboratory has a helicopter fuselage structural test facility at Ft. Eustis, Virginia, which is being used as the wind turbine blade test facility. Three

elements of the facility are used for the blade testing. One element is a "backstop" or structural support to which the blade sections are mounted in a cantilever fashion. The backstop consists of a 2" thick steel plate, 54" x 54" square, mounted to three vertical H beams. The H beams are structurally tied to additional H beams that run horizontally along the floor and are mounted on air cushions. The air cushions can be inflated or deflated to tune the natural frequency of the system. Figure 1 shows the backstop assembly with a typical blade mounted and ready for test.

The second element of the facility is the hydraulic loading system. This consists of a series of pumps supplying hydraulic fluid under pressure to a hydraulic cylinder(s). The hydraulic cylinder and plumbing can also be seen in Figure 1.

The third element of the facility is the control and data acquisition system. A closed loop analog controlled servovalve is used to proportion flow to the hydraulic cylinder in accordance with either stroke or load feedback signals. Data acquisition is controlled from the same computer network by measuring analog signals. Appropriate computer manipulation is applied to provide reduced output in a form such as maximum and minimum stress or cycle count.

#### LAMINATED WOOD BLADE TESTING

The testing of the laminated wood blade concept used two different specimens. The first was a prototype that simulated the early design of the laminated wood blade. The D spar, as shown in Figure 2, was made by laminating wood veneers to a male mold. A shear web was then bonded to complete the "D", and trailing edge panels were bonded onto the "D" to complete the airfoil. In subsequent wood blade development efforts, this method of construction was found to require too much hand labor in the fairing and finishing operation. Consequently, the concept shown in Figure 3 evolved and was used for fabrication of four blade sets (three of which are now operating on Mod-OA machines).

This current concept is to manufacture the blades in female blade-half-molds (an upper and lower half), and then to bond the two halves together. Structurally, the two concepts are identical, except for the details of the root end stud configuration. The first, or prototype specimen, initially used a stud as shown in Figure 4a. The embedded length was 15" of 1" x 7 Acme thread. External to the blade was a 5/8" NF threaded section that was designed to mate with the hub spindle on the Mod-O/OA machines. For the Ft. Eustis tests, the 5/8 studs were attached directly through the 2" thick backstop plate. This proved unsuccessful, as shown in Figure 5. Only 360,000 cycles at a root moment of 84,100 ft-lbs (maximum stud load of 10,000 lbs) were achieved prior to breaking 10 of the 24 studs. Examination of the failed studs and the test specimen indicated that failure had been caused not by the tensile

force in the studs resulting from the blade bending moment but by bending stresses in the bolts induced by bending of the backstop plate. Consequently, it was decided to reinforce the backstop plate by adding an extra H beam and to provide a very stiff, flanged, spool piece between the blade and the backstop. This spool piece, Figure 6, would be needed not only for testing, but for machine application. A spool piece was required for machine application because the Mod-OA flange was designed to mate with a similar flange on the original aluminum blades and was not stiff enough to support the wood blade directly.

The blade section was returned to Gougeon Brothers, Inc., the manufacturer who replaced all 24 studs with the configuration shown in Figure 4b. The blade section and a boilerplate spool piece were then sent to Ft. Eustis to continue testing. One million cycles were run at maximum stud loads of approximately 10,000, 13,750, and 17,500 lbs (root moments of 84,000, 115,500, and 147,000 ft-lbs, respectively). No evidence of structural degradation could be found. At that point, the root moment was increased to 210,000 ft-lbs (maximum bolt load of 22,000 lbs) and an additional 670,000 cycles were accumulated. At that point, 7 studs were found to have failed. Failure was due to the sharp corner and consequent high stress riser at the transition from the 1" threaded shank to the 1-1/2" diameter collar (see Figure 4b). No evidence of any wood failure or significant epoxy fatigue could be found. Subsequent examination of the blade proved that the laminated wood construction had come through the test completely unaffected. A plot of the test points achieved and their relationship to operating loads and numbers of cycles is shown in Figure 7.

At that point, testing of individual studs had led to the development of a completely new stud design as shown in Figure 4c. (A complete description of the testing of individual studs is contained in Ref. 1.) In addition, a new blade manufacturing concept had evolved and NASA contracted with Gougeon Brothers, Inc. to manufacture a second fatigue test specimen utilizing the latest design concept (see Figure 3). This specimen was tested in a manner identical to that used for the first specimen with two exceptions. First, a spool piece identical to that used for Mod-OA operation was used instead of the boilerplate spool. The other difference was that a Linear Variable Differential Transducer (LVDT) was mounted on the spool piece to detect any change in spring constant across the interface. A photograph of a typical LVDT mounting is shown in Figure 8. However, the initial load of 12,500 lbs shear (269,000 ft-lbs) was selected to be high enough to insure failure in some element of the wood. This load was equivalent to that projected for the hurricane load case. Control of the blade loading was accomplished by controlling the blade test section tip deflection to a constant amplitude. As can be seen from the root bending moment curve in Figure 9, the wood blade did experience structural failure under this load condition. However, more than 20,000 load cycles were achieved before structurally significant damage occurred. And, the blade sustained

more than 100,000 cycles to root moments in excess of 225,000 ft-lbs before significant drop-off of load carrying capability was experienced. The LVDT data plotted in Figure 10 indicate that some deterioration of the root end was occurring even at a low number of cycles, since the gap opening was steadily increasing. Relatively speaking, the change in gap opening was minor, changing only .014 inches in 43,000 cycles, or .0003" per thousand cycles. When compared to the initial value, this is a change of 2% per 1000 cycles. However, at about 90,000 cycles, the rate of change took a sudden increase, which indicates that major structural damage had occurred. It took another 25,000 cycles before this damage was serious enough to cause significant loss in load carrying capability (see Figure 9).

Consequently, the LVDT is felt to be a very sensitive tool for monitoring blade structural degradation and the concept is being used on all Mod-OA machines. Under normal operating conditions, the gap opening (or closing) is a constant value for a given set of operating loads. Any change would be reason to suspect potential blade problems. And, a limit switch could be used (and is installed on several Mod-OA machines) to effect an automatic shutdown. At the present time, however, there is no reason to suspect a problem with laminated wood blades on Mod-OA wind turbines. As is shown in Figure 7, the test data for both the prototype and the revised wood blade test section supports the design allowable curve selected for relating the maximum allowable bolt loads to an expected number of operating cycles. In addition, Figure 7 also shows that the design allowable curve lies substantially above the load/cycle data that is predicted by machine operating experience. Consequently, it is believed that the fatigue testing of sections at Ft. Eustis has proved that within the operating regimes of the field machines the blades should last for at least the design lifetime.

It should be pointed out that the fatigue testing of root sections does not simulate environmental effects that could accelerate structural degradation. Nor do the root end fatigue tests necessarily demonstrate fatigue strength of the blade material in the basic airfoil section. And, obviously, the fatigue tests do not demonstrate buckling capability. All of these items must be tested separately, the combination of tests then validating the blade capability. But in most cases, it is the blade root end that is of the greatest concern and is the most difficult to test. Additional data that support the effectiveness of the Ft. Eustis method of testing WTG blade sections are presented later in this report with the discussion of the aluminum blade testing.

#### STEEL SPAR BLADE

The concept of using a tapered steel spar (such as a utility pole) as the primary structural member of a wind turbine blade has existed for some time. In 1978 the requirement of a new set of blades for the

Mod-0 wind turbine resulted in the design and fabrication of two blades based on this concept. A description of these blades and their performance on Mod-0 is given in Reference 3. The details of the blade construction are shown in Figure 11 and a picture of the blades mounted on the Mod-0 WTG can be seen in Figure 12. A structural analysis of the steel spar blade design showed that the critical area in fatigue was the root end weld. This weld connects the spar to the flange required for bolting the blade to the hub.

Application of standard welding codes, such as the Structural Welding Code, to this weld resulted in the requirement of close interval (100 hour) inspections. To better ascertain inspection requirements of this weld, a root end specimen was tested in the Ft. Eustis facility. In addition, a prototype of a second root end design was also tested. This design consisted of a double wall at the root end. The outer tube was swaged over the inner tube. The purpose of the double wall was to reduce the stress in the critical spar-to-flange weld. Sketches of both the single wall and double wall specimens are shown in Figure 13. The results of these tests and the conclusions drawn from them follow.

#### Single Wall Steel Spar

The single wall steel spar consisted of a flange that was machined from rolled plate and a tapered tube of manufacture similar to that used for utility poles. Schedule requirements made it necessary to use available rolled plate for the flange rather than more desirable forged material. The tube was joined to the flange with a high quality weld. Weld soundness was established by radiographic inspection.

The spar was load cycled for  $10^6$  cycles at each step of increasing load until failure occurred. Failure occurred after 265,000 cycles at the fourth load level. This is shown graphically in Figure 14. The stress level indicated on the graph was calculated using simple beam theory. Failure occurred in the flange radius. Failure here rather than in the weld is attributed to the low strength of the plate material from which the flange was machined and the orientation of the grain structure with respect to the applied stress. Figure 15 compares the grain structure of the plate material with that of a forged material. The plate material was stressed transverse to the grain direction. Fatigue strength transverse to the grain direction has been shown to be significantly less than that parallel to the grain direction (Ref. 4). The forging process eliminates elongated grain structure and reduces fatigue strength sensitivity to stress direction. Subsequent flanges for spar blades have been machined from forgings.

Because failure occurred outside the weld area, the fatigue strength of the weld was not determined. However, certain conclusions can be drawn by comparing the test results to the fatigue stress levels allowed by the Structural Welding Code for tubular structures

(Ref. 5). In Figure 14 the single wall test results can be compared to three weld categories: Category A is plain, unwelded pipe; Category B is for butt splices with full joint penetration where the weld is ground flush and inspected by radiograph or ultrasound; and Category C is the same as B without the grinding and inspection requirements. The original inspection interval of 100 hours was set using Category B allowables. As the figure shows, the test data exceed Category A allowables. Therefore, a new inspection interval of 300 hours was set based on Category A allowables. It should be noted that in earlier versions of the Structural Welding Code, a high quality welded joint could be placed in Category A.

The Ft. Eustis test results verified that it was legitimate to apply the Structured Welding Code to a structure of this type. However, only a lower bound for fatigue strength was obtained. The actual strength will be obtained only with additional testing.

#### Double Wall Steel Spar

The purpose of the double wall steel spar was to reduce the stress in the critical flange weld by increasing the wall thickness. After cleaning mating surfaces, a short section of tapered tubing was hydraulically swaged over a longer piece of tapered tubing using commercial utility pole fabrication techniques. The end was trimmed and welded to a flange. The wall thickness at the weld was twice that of the single wall spar discussed above.

The double wall spar was tested in the same manner as the single wall spar. The initial load level was the highest load level that survived  $10^6$  cycles with the single wall spar. The spar survived this test and the load was increased to the level that caused failure in the single wall spar. After 380,000 cycles, the test was stopped because of severe circumferential cracking in the weld and adjacent metal, and longitudinal cracking in the tapered wall portion of the outer tube. A photograph of the crack in and near the weld is shown in Figure 16.

Analysis of the failure consisted of examining strain gage data and reviewing the Structural Welding Code in an attempt to categorize the double wall spar weld. In Figure 17, calculated strain is compared with measured strain on the outer tube. The calculated strain assumed the outer tube was fully effective in bending except in the tapered outboard section. The figure shows that the outer tube is much less than fully effective, which means the inner tube is picking up additional load. The high strain gradient near the weld indicates high shear stresses at the weld. The measured strain just inboard of the weld is very close to that calculated and about half that measured on the single wall spar for the same applied load.

The stress history for the double wall spar is shown in Figure 14. Examination of the Structural Welding Code showed there was no category that precisely matched the weld in question. It was clear,



however, that there was a substantial reduction in allowable stress in structures where doublers were used and where shear in a weld was present. It was concluded that while the double wall reduced the nominal stress in the weld, this was more than offset by the stress concentration inherent in this type of weld.

#### TFT FIBERGLASS BLADE

Details of the TFT Fiberglass blade were presented in the paper by Weingart. To provide a brief review, planform and cross sectional views of this blade are shown in Figure 18. The root end retention of the TFT fiberglass blade is shown in Figure 19. After applying a film adhesive, epoxy impregnated fiberglass was wound over the steel retention ring. Curing of this assembly provided an adhesive bond between the fiberglass and steel. To provide redundancy, the fiberglass was also mechanically locked into the retention ring. This was done by using hoop wraps to force the TFT into the depressions in the retention ring.

To reduce costs, half scale specimens were used for fatigue testing. A sketch of the specimen is shown in Figure 20. Two specimens were fabricated; the first specimen (bonded) was fabricated in the same manner planned for the full scale blade while a release agent was applied to the retention ring of the second specimen (unbonded) so that the retention capability of the mechanical lock could be tested.

#### Load Scaling

In subscale tests, the applied loads must be scaled down so that the applied stress is the same as in the full-size article. For an end loaded cantilever beam, the load scales according to the square of the scaling factor, if both cross section and length are scaled. For example, a half scale beam requires  $1/4$  the end load of a full-size beam to produce the same bending stress. To match the shear stress also requires  $1/4$  of the load. In some root end designs, the bending moment is the predominant failure-causing load. However, in a bonded joint such as that at the root of the fiberglass blade, the shear load is also important.

To provide both the desired shear and bending stress at the root end of a full size fiberglass blade would require a specimen 30 feet long. For a half scale test, the required length would be 15 feet. Because the half scale specimens were only 13 feet long, it was not possible to provide both the desired bending stress and the desired shear stress using a single shear load. Cost and schedule requirements did not allow the design and fabrication of a specimen where two or more shear loads could be introduced. The tests were conducted matching the desired bending stress. This resulted in the desired shear stress being exceeded by about 15 percent.

### Test Parameters

The test load sequence and number of cycles for both specimens are tabulated in Table 1. After surviving the initial loading spectrum, the bonded specimen was rotated 90° about the pitch axis and the load cycling continued in an attempt to achieve  $1 \times 10^6$  cycles at each load level. This specimen was rotated 90° so that the effect on the bond of the first set of load cycles would be preserved for later examination. The unbonded specimen was cycled in the same orientation throughout the entire test.

The bonded specimen was tested at a rate of 5 cycles per second (Hz). The initial rate used for the unbonded specimen was the same. However, when heat buildup was detected in the retention area, the rate was decreased to 3 Hz. No heat was detectable at the lower cycle rate.

### Test Results and Conclusions

After  $4 \times 10^6$  cycles at lower load levels, both specimens failed after about 350,000 cycles at the hurricane load level. (The hurricane load was defined as a pressure of 50 pounds per square foot applied flatwise to the blade.) In both cases, failure took place in a 1/16 inch flange fillet (Figure 20). Visual and tap test inspection of both specimens revealed no apparent damage in the retention area other than the flange failure. Definitive determination of damage will require sectioning of this area. This is planned for the near future.

During initial load cycling of the unbonded specimen motion was detected between the composite and steel retention. As the test progressed, this motion decreased even though the load was periodically increased. This behavior is shown graphically in Figure 21 where the compliance at the tip of the beam (deflection per unit of applied load) is plotted against number of cycles. The plot shows the compliance steadily decreasing for the first half million cycles. This behavior was probably caused by the composite being wedged on the tapered portions of the steel retention ring. If it had been possible to run the test with reversed bending, it is likely that high tip compliance and motion between composite and steel would have been observed during the entire test.

Compliance data for the bonded specimen after it had been cycled  $2.22 \times 10^6$  times and rotated 90° is also shown in Figure 21. On average, the compliance of the bonded specimen is about 10 percent less than that of the unbonded one. Also, the data scatter for the bonded specimen is less. This kind of behavior would be expected. After about  $4.5 \times 10^6$  cycles both specimens showed a very rapid increase in compliance. This is related to the failure in the flange fillet.

The results of these two tests gave high confidence in the ability of the fiberglass blade root end to successfully withstand the operating loads. After testing of the bonded specimen was complete, no damage to the bond was observed. The second test showed that if the bond failed, the mechanical retention was capable of withstanding operational loads.

#### ALUMINUM BLADE TEST

As mentioned earlier, fatigue testing of blade sections is not considered to be a quantitative test in that it will not predict the number of hours a blade will operate satisfactorily on a field machine. This type of testing is, however, very effective in highlighting design deficiencies or over-stressed areas (structural "hot spots") in specific blade locations (generally the root area). As a means of proving test effectiveness, one of the aluminum blades from the original three blades built for the Mod-0 (100kW) wind turbine was modified to be a fatigue test specimen. Details of the blade design and construction are contained in Reference 6. The modification consisted of cutting the 62.5 foot-long blade approximately 21 feet from the root end flange. The cut section was then reinforced for introduction of shear loads by slipping on a one-inch thick aluminum plate (with the airfoil section cut out of the middle) and rigidly fixing the skins, stringer, and trailing edge channel to the plate. Another one-inch thick aluminum plate (without airfoil cut out) was then bolted to the attached plate. This provided a flat surface, normal to the blade spanwise axis, on which the clevis for attaching the hydraulic cylinder could be mounted. A photo of the modified blade section mounted in the Ft. Eustis facility is shown in Figure 22.

To determine the loadings for the test series, the flatwise and edgewise moments at station 81.5 were combined vectorially as per predictions of the MOSTAB-HFW computer code for the Mod-0 blade in Mod-0A service. This established a relative direction and magnitude for a single shear load to be applied at the tip of the test specimen. The relative direction of the shear force line was  $49^{\circ}$  to the chord line of the Station 81.5 rib. The magnitude of the first shear force to be applied would be such as to produce a station 81.5 moment of 103,000 ft-lbs (maximum aluminum stress = 7340 psi). Subsequent load steps were to be such as to produce moments of 135,800 ft-lbs (9620 psi) and 164,800 ft-lbs (12,000 psi). The 7340 psi stress level represents what would be considered an infinite life fatigue stress (R-ratio = 0.01) while the 9620 psi figure was what would be expected as a maximum stress under the 40 MPH, 40 RPM operating conditions. The third stress level, 12,000 psi, was selected by arbitrarily placing a factor of 1.25 on the 40 mph, 40 RPM case. This turned out to be immaterial, however, since the testing never proceeded to that load level.

Testing was started with a shear load of 5900 pounds required to produce the Station 81.5 moment of 103,400 foot/pounds. This load level should have produced no problems in the aluminum blade based on design capabilities. However, as soon as testing started, it was evident that the root end load transfer from the innermost rib (Station 48) to the gunbarrel section (Figure 23), was inadequate. Considerable scraping and wear began immediately. This was directly comparable to what had already been experienced in the field and had resulted in the incorporation of a shim (or bearing surface) with high hardness and low coefficient of friction between the steel root end fitting and the aluminum rib at Station 48. Testing was allowed to continue at the 5900 pound shear level with the intention of shimming the Station 48 rib as soon as wear became excessive. A cyclic rate of 2 Hz was maintained; at about 500,000 cycles a loud popping noise was heard. A similar noise was heard again at about 900,000 cycles. One million cycles were completed without obvious external cracks, although it is probable that internal damage had occurred. Wear, as shown in Figure 23, had not progressed to the point where shims were required.

The shear load was increased to 7900 pounds, which represented the 40 MPH, 40 RPM case, and several more loud popping noises were heard immediately. After only a few hundred cycles, a skin crack was noticed in the trailing edge, extending 6 inches into the D spar skin. The extent of the crack is shown in Figure 24. The test was allowed to continue for another 55 minutes or until a total of 8778 cycles had been accomplished at 7900 pounds. At that point, the crack had grown further into the D spar skin and testing was terminated. The blade was removed from the test stand and returned to LeRC for inspection, which resulted in the following observations (refer to Figure 24):

1. The crack extended from the trailing edge through an internal splice plate at Station 88 all the way forward and 14 1/2 inches into the intermediate (D spar) skin.
2. The aft stringer was broken.
3. The middle stringer was broken.
4. The crack also extended up into the shear web for about half the blade thickness (10 inches).
5. The crack terminated in a rivet hole in the forward stringer.
6. The forward stringer was not broken.

This type of failure was typical of a particular mode of failure that was experienced on the Mod-OA machines. Dusting of rivets in the trailing edge skins was also typical of blades in the field. The test section, however, did not exhibit rivet dusting since the test blade section had a trailing edge skin that was much thinner than the

Mod-OA blade, and there were no trailing edge stringers. Therefore, not as much load was being transferred through the skin into the rivets and dusting did not occur. Also, the Ft. Eustis specimen did not experience Station 81.5 rib cracking as was seen in the field. The rib cracking of the blades in the field was caused by wear of the Station 48 rib, which in turn forced bending loads into the Station 81.5 rib. Thus, since wear did occur in the test section, it is believed that had additional load cycles been applied to the blade, station 81.5 rib cracking would have been a certainty. To put additional cycles on the blade would, however, have required a major repair of the cracked skin and stringer and was not considered to be warranted.

Testing of the Mod-0 aluminum blade section was thus considered to have validated the fatigue testing concept being used at Ft. Eustis. Structural "hot spots" were identified; had this testing been conducted early in the aluminum blade fabrication effort, appropriate design modifications or structural fixes would have been made. It is probable that this type of testing would have prevented premature blade damage as was experienced in the field.

## CONCLUSIONS

The following are general conclusions based on the blade testing experience at the Ft. Eustis facility and the correlation of the aluminum blade test data with operational experience in the field.

1. Fatigue testing of Mod-0/OA size root end sections in cantilever bending to  $1 \times 10^6$  cycles at a series of loads representative of the peak loads that wind turbines will see in service is an effective way to identify design deficiencies or structural "hot spots."
2. Cyclic test rates of 2 to 6 Hz on large blade sections can be achieved. This allows a root end concept to be structurally verified in a matter of 3 to 6 weeks of testing.

The following conclusions are specific to the different blade types listed.

1. The joining of laminated wood blades to the wind turbine hub through bonded studs provides a structurally sound system. Thousands of cycles at loads in excess of the hurricane load can be achieved without structurally significant damage. Use of LVDT's and/or limit switches is a very sensitive system for detecting failure of the bonded stud joint.
2. Should cracking and structural failure of the root end joint of a laminated wood blade occur, the failure mode is benign rather than catastrophic.

3. Test of a single wall steel spar showed that designing to the Structural Welding Code was conservative. To determine the actual fatigue strength of the critical spar weld requires additional testing.
4. Test of a double wall steel spar showed that, while the nominal stress in the weld was reduced, this was more than offset by the stress concentration inherent in this type of weld.
5. Half scale tests of the fiberglass blade root end showed that both the primary retention (bonding) and secondary retention (mechanical lock) are individually capable of withstanding the operational load spectrum without failure.
6. For the aluminum blade sections tested, the fatigue test damage correlated closely as to type and rate with the damage that was experienced in the field.

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Table 1. Fatigue Load History of Half-Scale  
Fiberglass Blade Retention Specimens

Significance of Load	Peak Applied Moment, lb-ft	Peak Applied Shear, lb	No. of Cycles	
			Bonded Specimen	Unbonded Specimen
Design	19,000	1440	10 <sup>6</sup>	10 <sup>6</sup>
High wind	22,000	1670	10 <sup>6</sup>	10 <sup>6</sup>
Normal Shutdown	24,500	1860	2 x 10 <sup>5</sup>	2 x 10 <sup>5</sup>
Emergency Shutdown	28,500	2165	2 x 10 <sup>4</sup>	2 x 10 <sup>4</sup>
Hurricane	42,000	3190	100	100
			(a)	
Normal Shutdown	24,500	1860	8 x 10 <sup>5</sup>	8 x 10 <sup>5</sup>
Emergency Shutdown	28,500	2165	9.8 x 10 <sup>5</sup>	9.8 x 10 <sup>5</sup>
Hurricane	42,000	3190	3.6 x 10 <sup>5</sup> (b)	3.8 x 10 <sup>5</sup> (b)

(a) Specimen rotated 90°  
(b) Specimen failed

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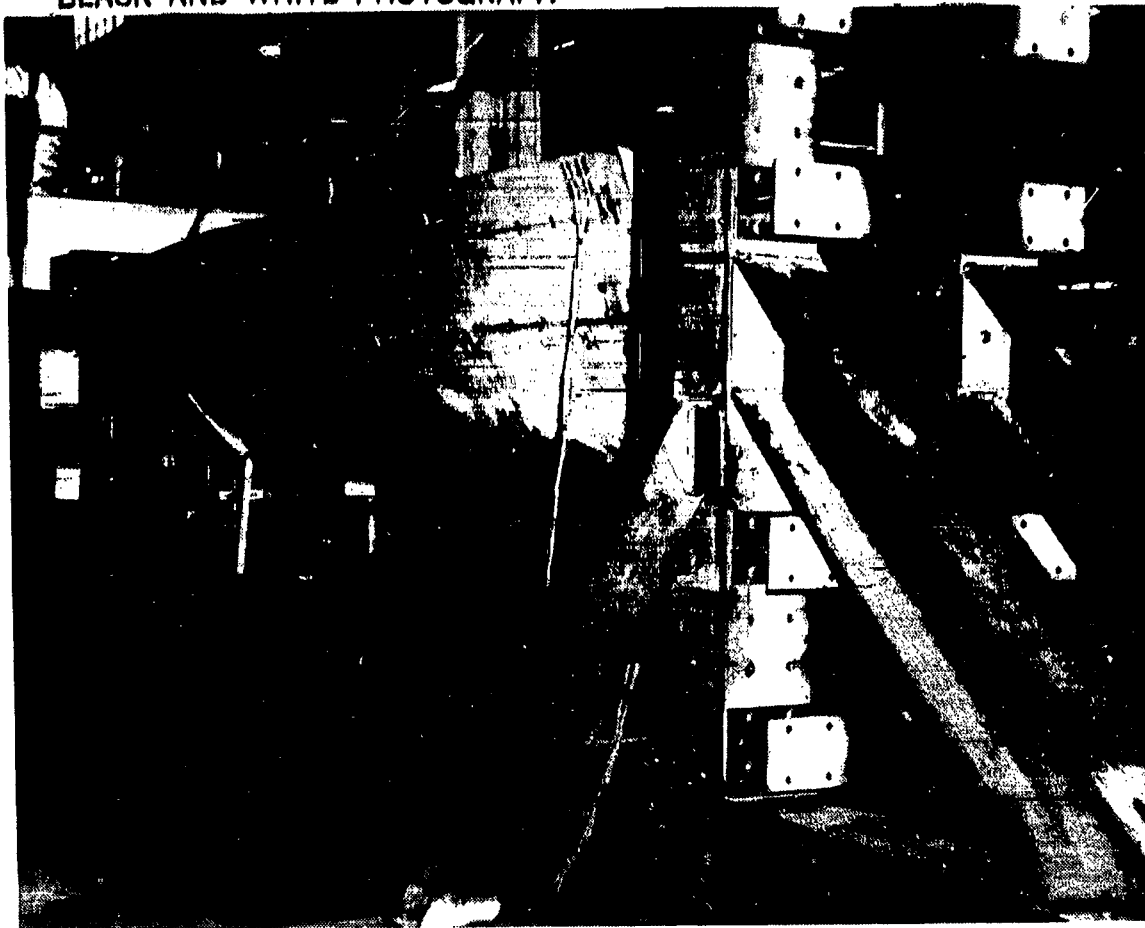


Figure 1. - Wind turbine blade test facility at Ft. Eustis, Virginia.

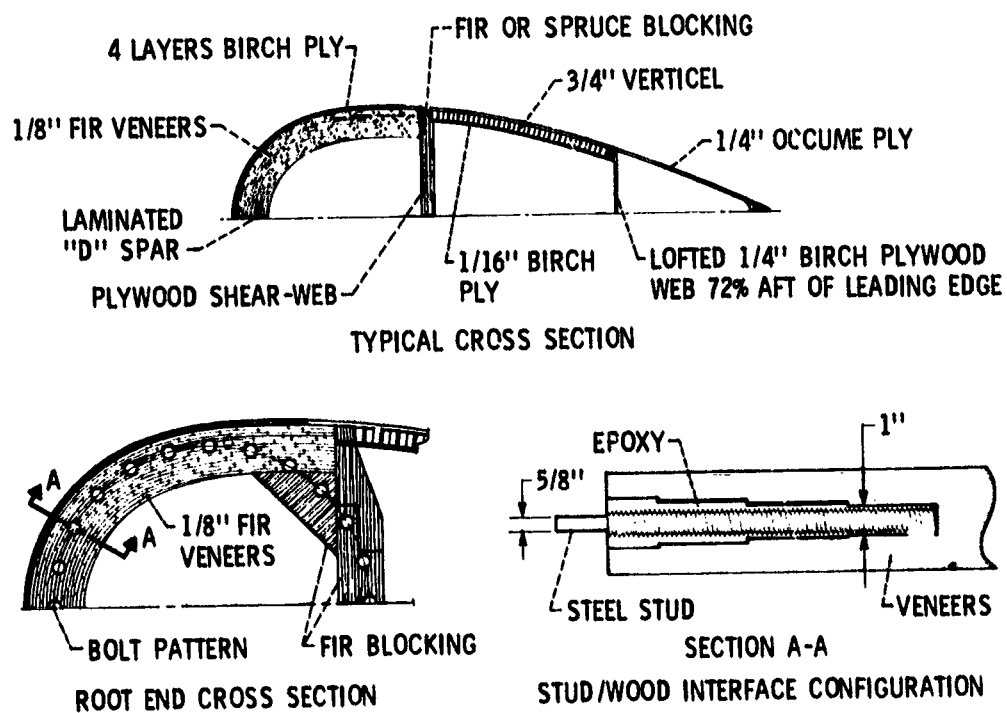


Figure 2. - Prototype wood blade concept.



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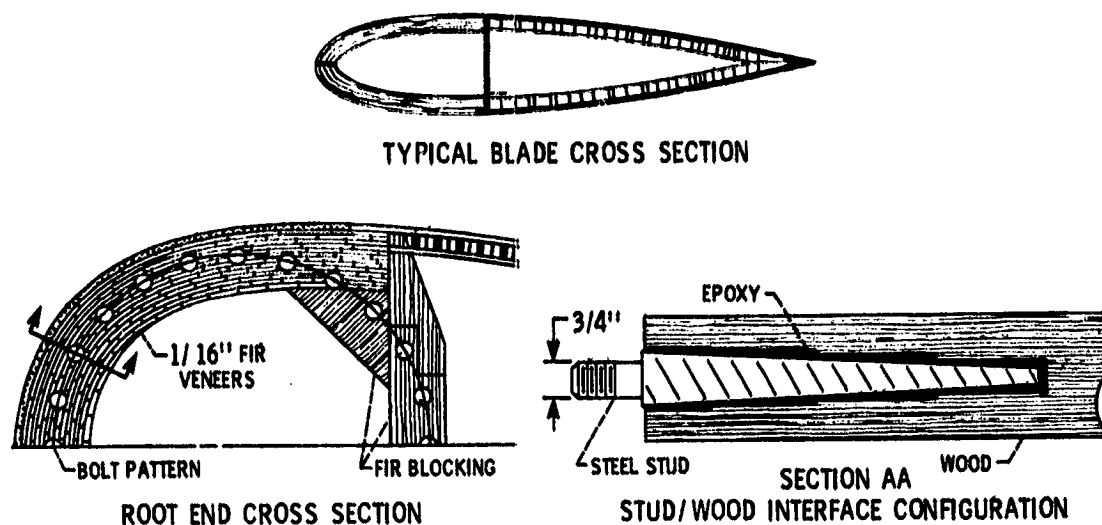
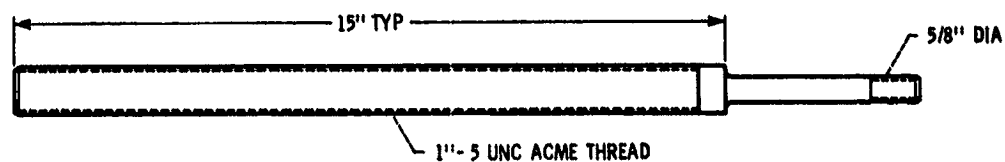
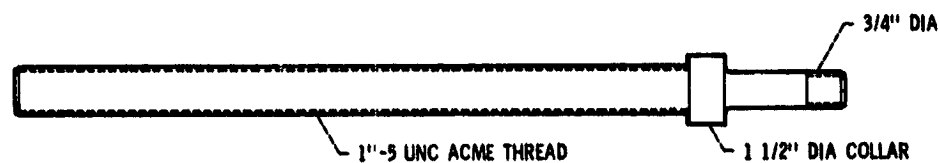


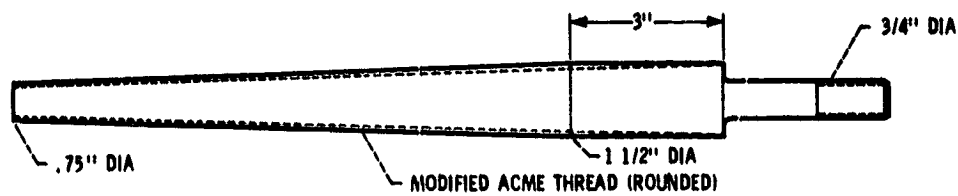
Figure 3. - Final design of laminated wood blade.



(a) Prototype blade stud design #1



(b) Prototype blade improved design stud



(c) Current stud design used for 2nd blade section and Mod-OA blades

Figure 4. - Stud design history.

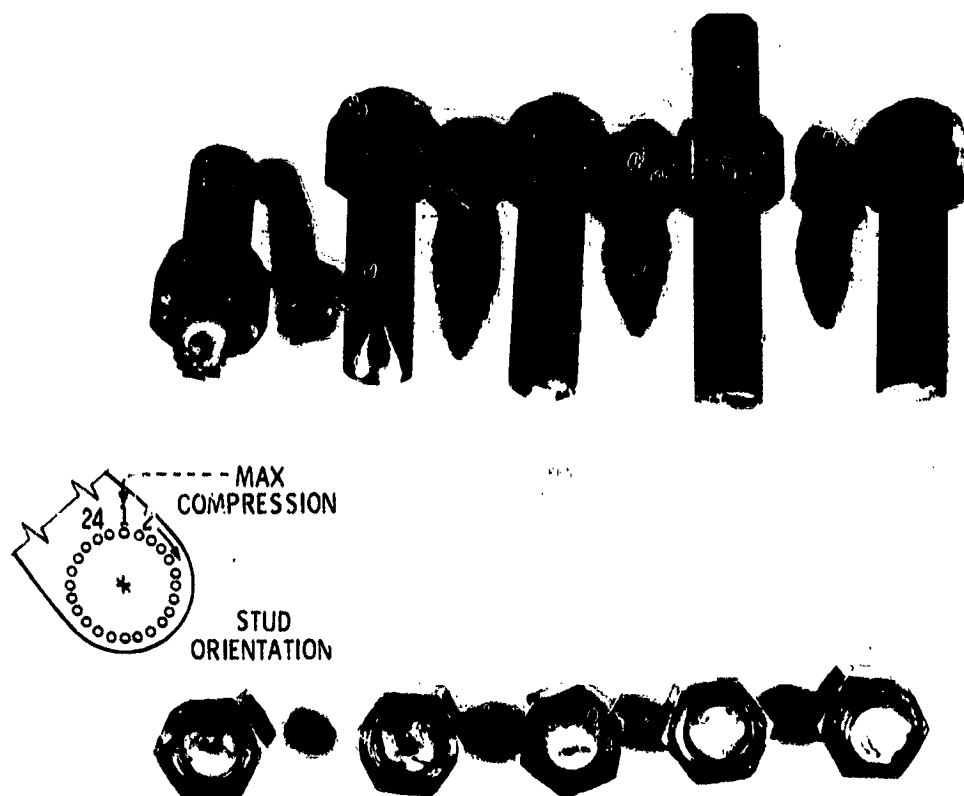


Figure 5. - Broken bolts from first test of prototype wood blade section.

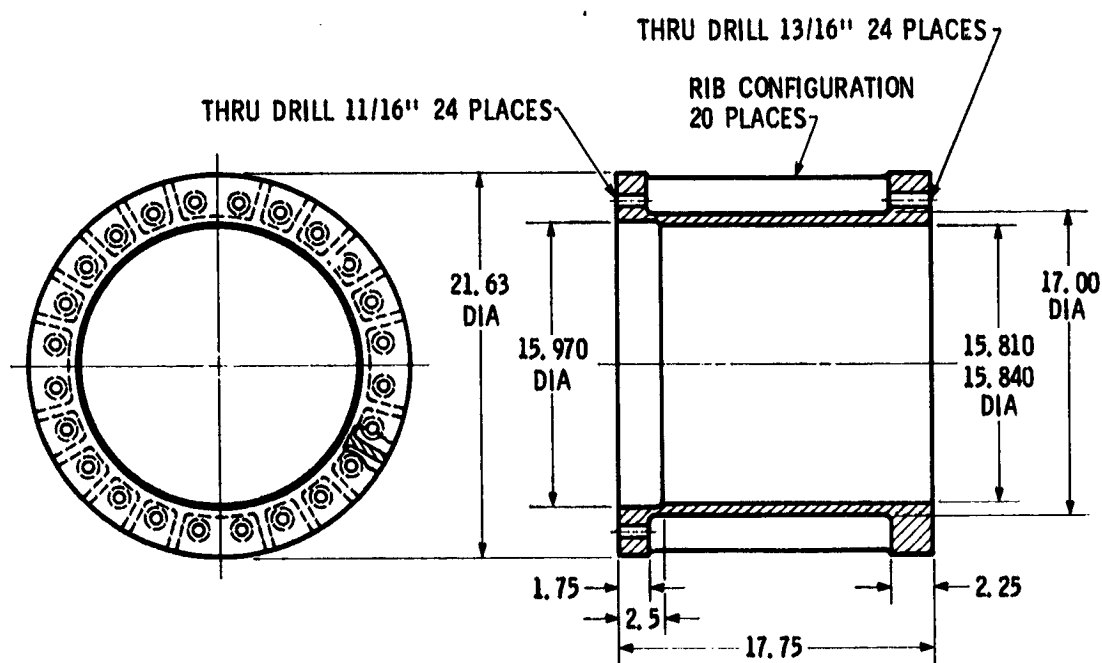


Figure 6. - Laminated wood blade root end adapter.

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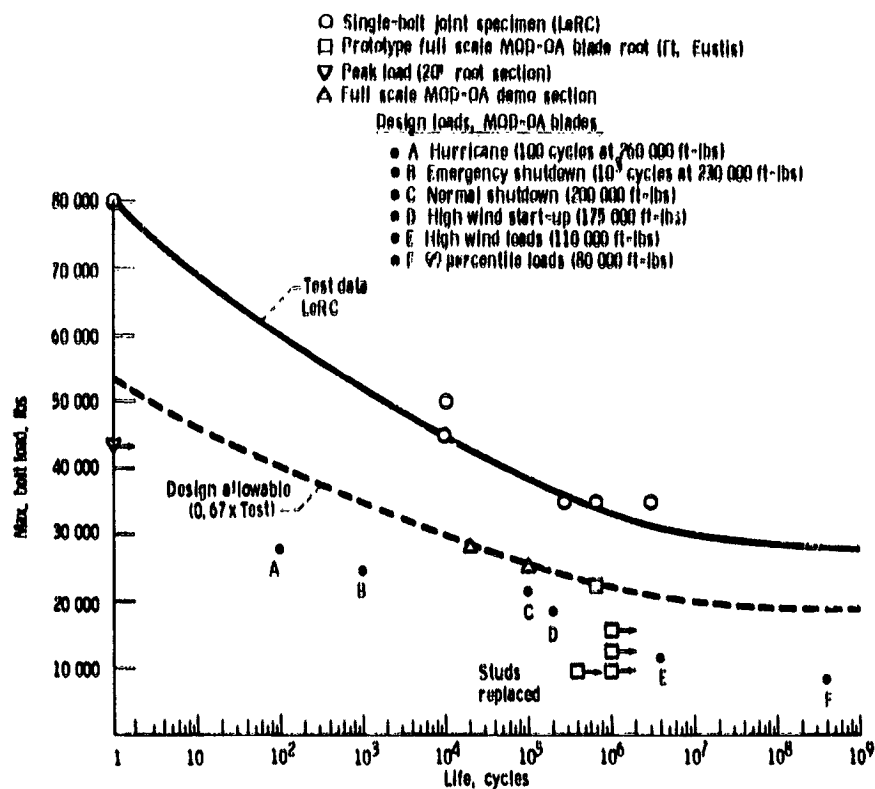


Figure 7. - Bolt-to-wood tension joint fatigue data.

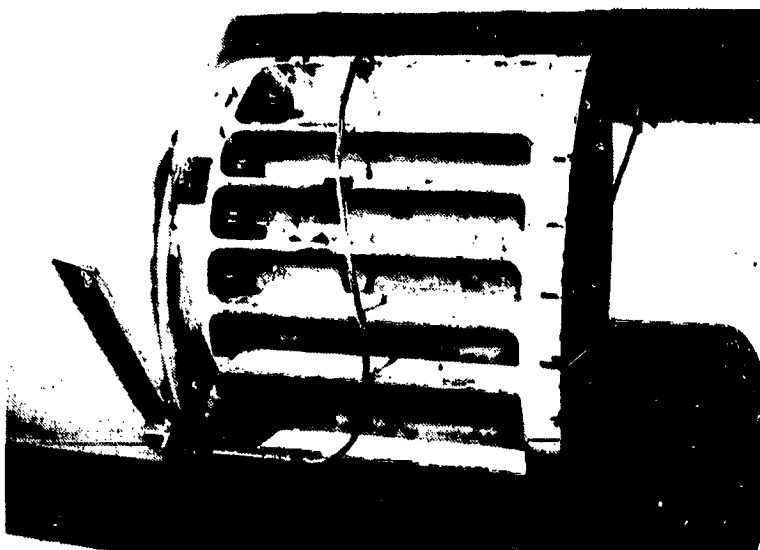


Figure 8. - LVDT mounting on wood blade root end.

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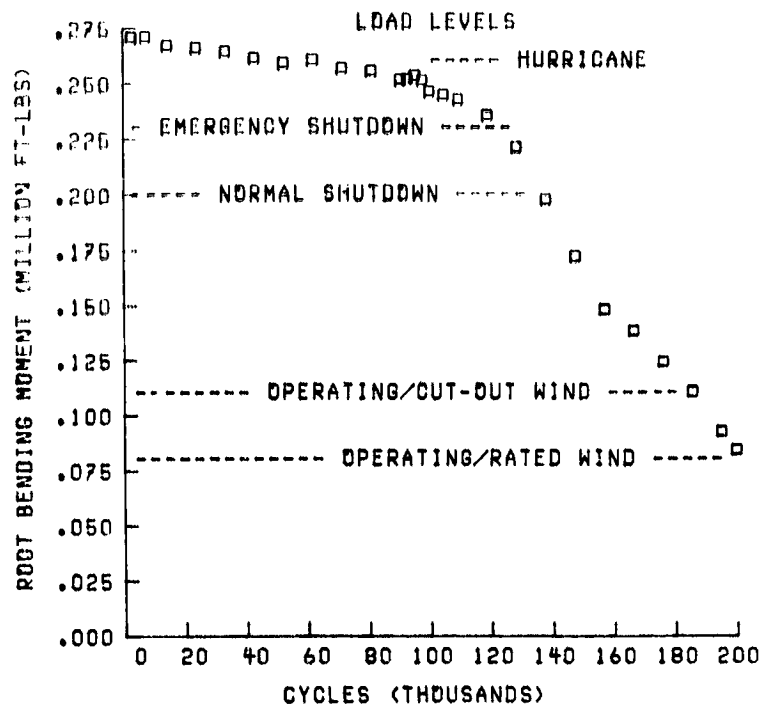


Figure 9. - Stiffness degradation during fatigue test of laminated wood blade.

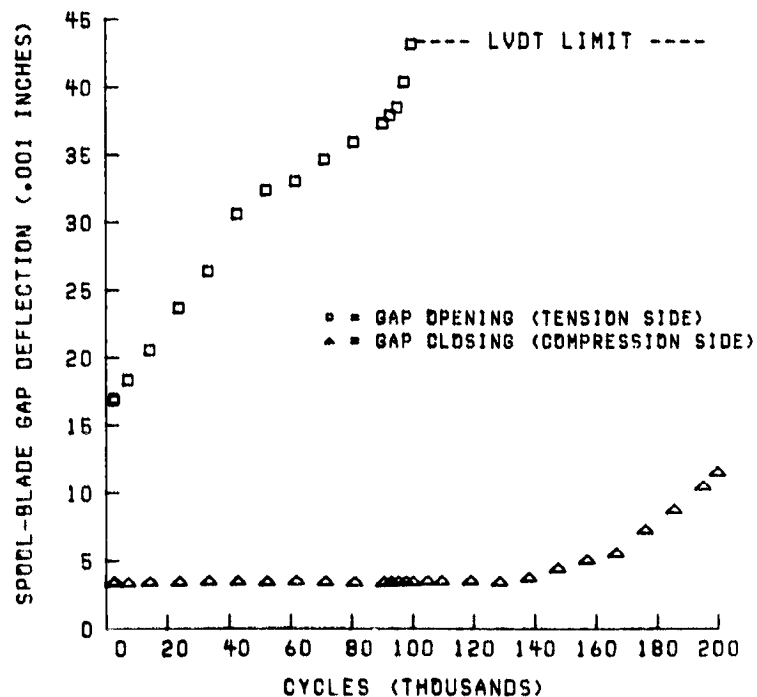


Figure 10. - Sensitivity of LVDT in measuring wood blade root end fatigue damage.

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Figure 11. - Fabrication procedure for steel spar (utility pole) blade.

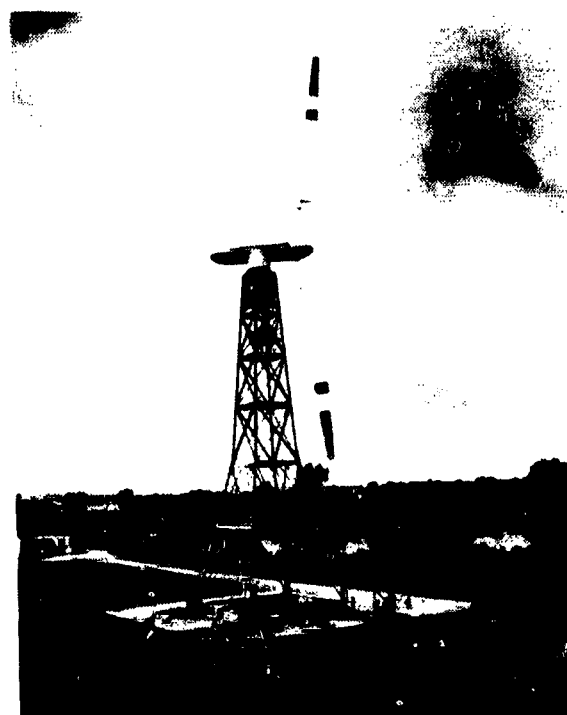


Figure 12. - Steel spar blades mounted on Mod-0 wind turbine.

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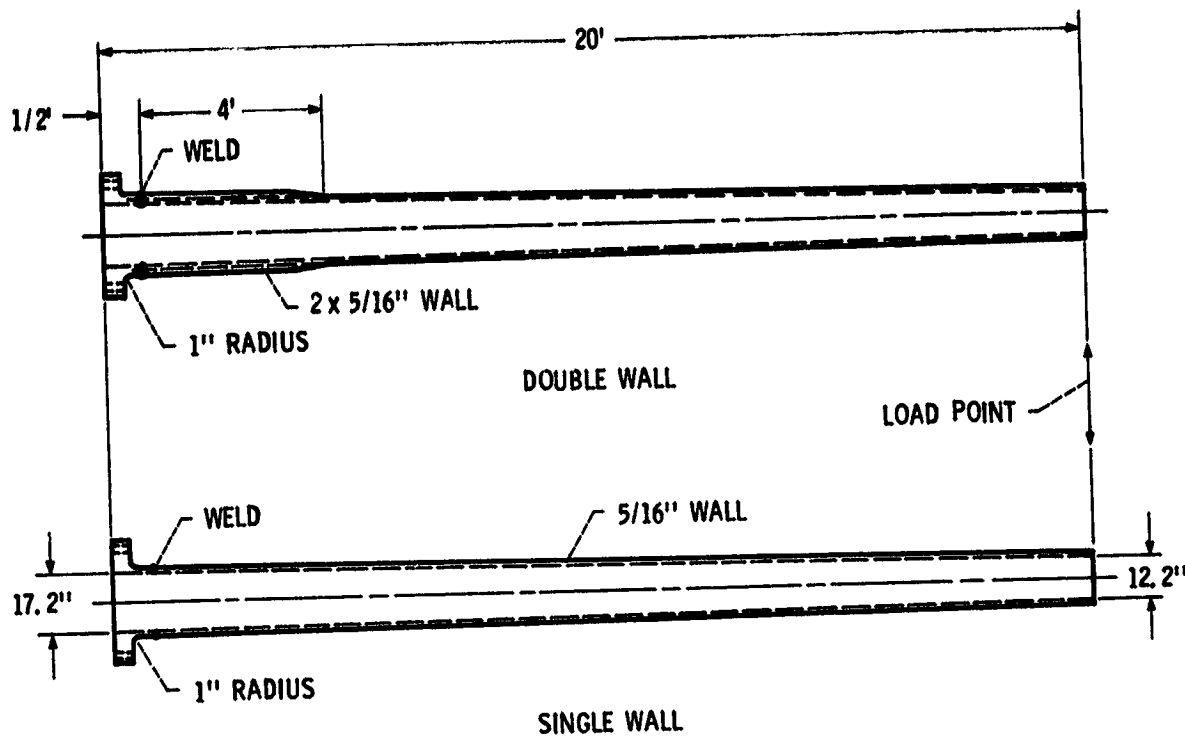


Figure 13. - Steel spar test specimens.

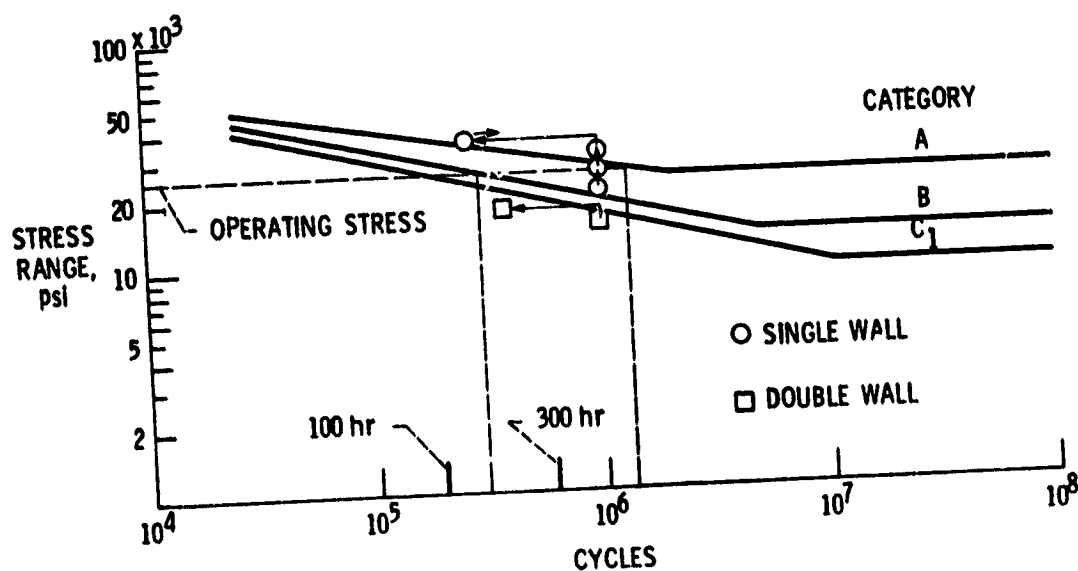


Figure 14. - Comparison of steel spar test results to Structural Welding Code allowables.

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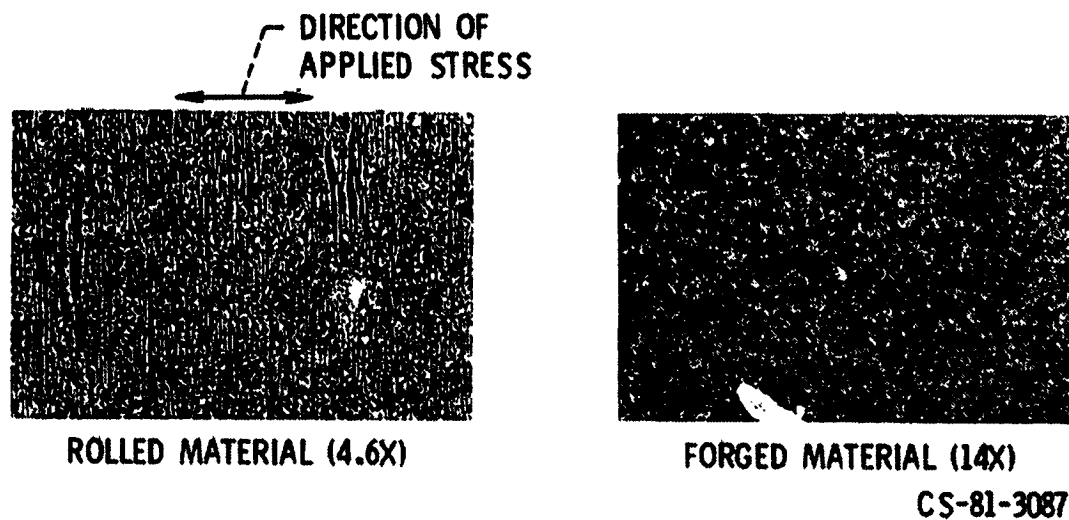


Figure 15. - Comparison of steel flange material grain structure used for steel spar blades.



Figure 16. - Weld crack resulting from fatigue test of double wall steel spar.

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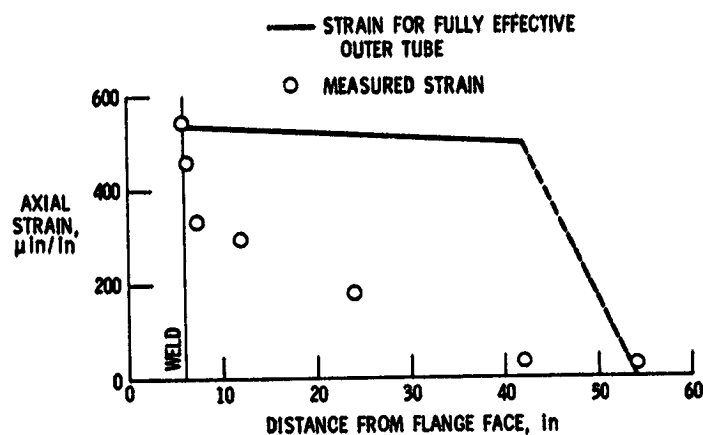


Figure 17. - Comparison of calculated and measured strain in double wall steel spar for an applied load of 10,000 lb.

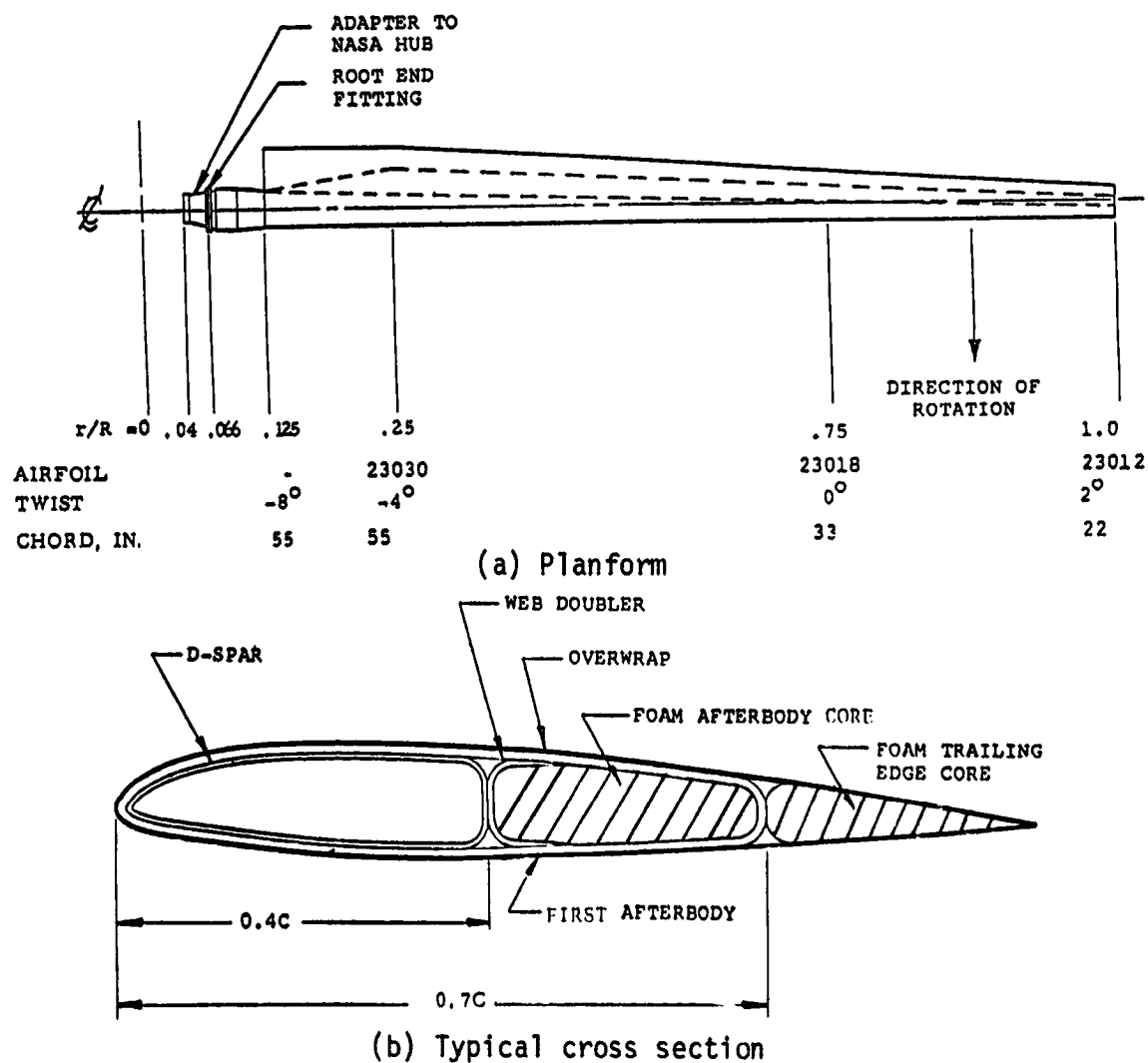


Figure 18. - Composite blade geometry definition.



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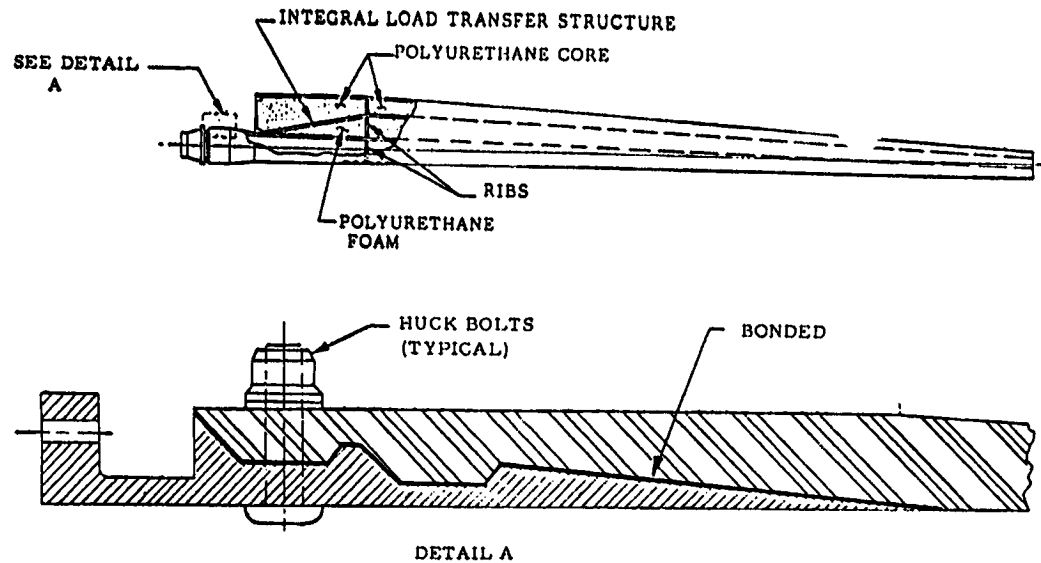


Figure 19. - Composite blade root end retention details.

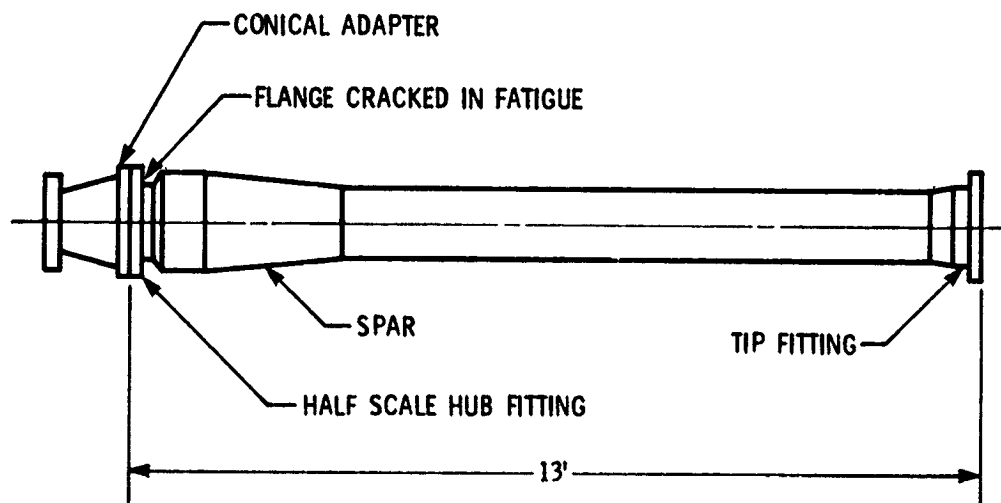


Figure 20. - Half scale composite blade hub joint fatigue test specimen.

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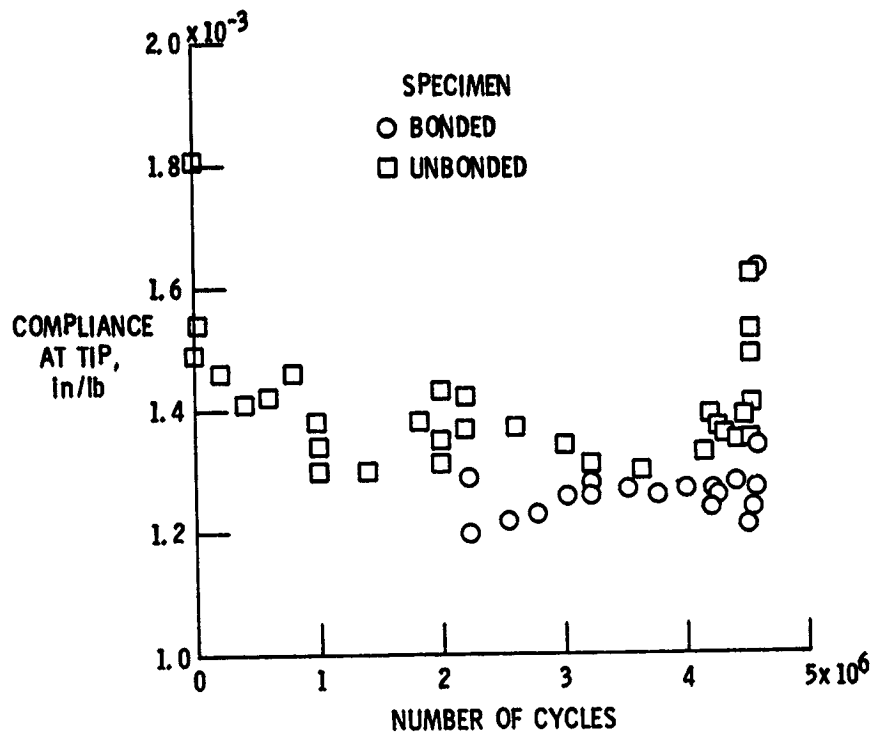


Figure 21. - Effect of load cycling on compliance of fiberglass fatigue specimens.

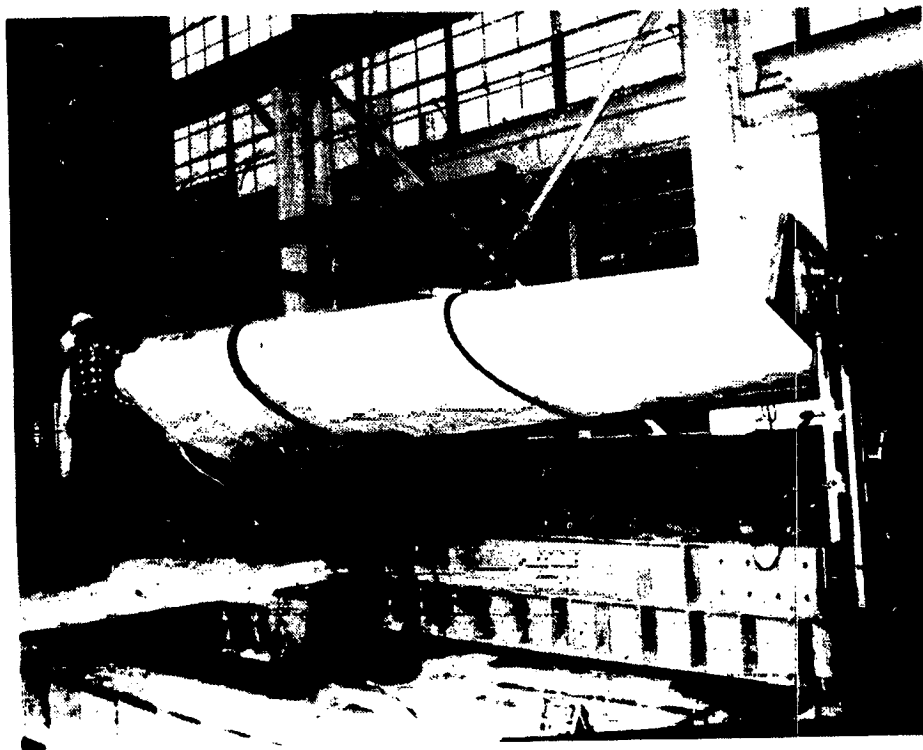


Figure 22. - Mod-0 aluminum blade mounted in the Ft. Eustis facility.

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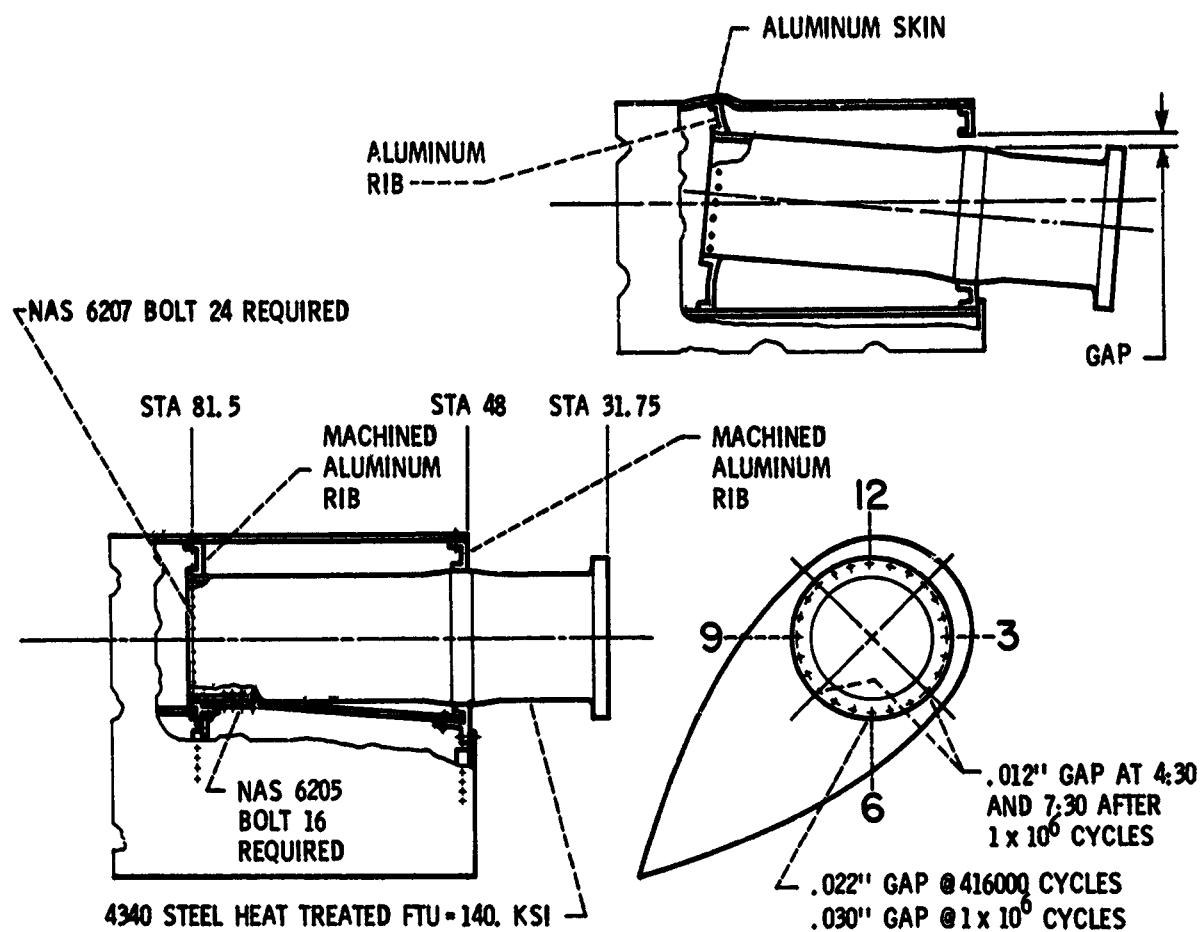


Figure 23. - Mod-0 aluminum blade root end details and wear pattern.

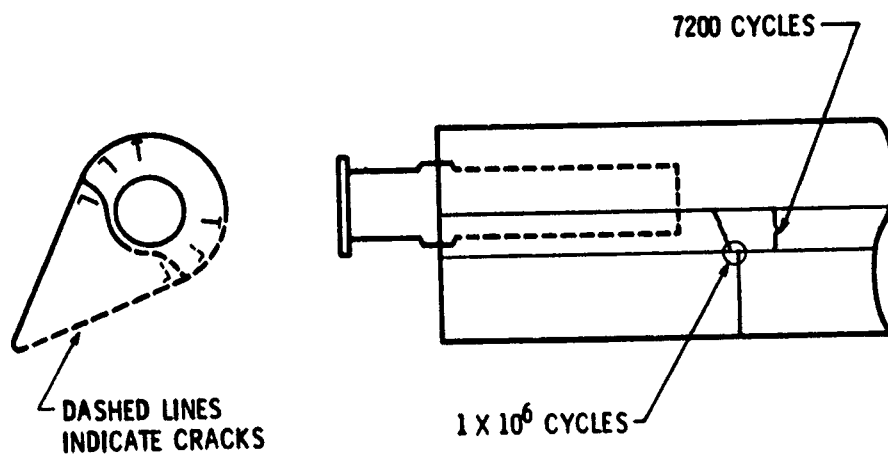


Figure 24. - Damage resulting from fatigue test of Mod-0 aluminum blade.

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LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Meteorological Characteristics for Design and Operations

Session Chairman - A. H. Miller (Pacific Northwest Laboratory)

"Wind and Turbine Characteristics Needed for Integration of Wind Turbine Arrays  
into a Utility System"

G. L. Park  
(Michigan State University)

"Long-Term Energy Capture and the Effects of Optimizing Wind Turbine Operating Strategies"

A. H. Miller  
W. J. Formica  
(Pacific Northwest Laboratory)

"Integration of Wind Turbine Generation (WTG) into Utility Generating Systems"

T. F. McCabe  
M. K. Goldenblatt  
(JBF Scientific Corporation)

"The Useful Potential of Using Existing Data to Uniquely Identify Predictable  
Wind Events and Regimes - Part I"

D. W. Trettel  
J. T. Aquino  
T. R. Piazza  
L. E. Taylor  
D. C. Trask  
(Murray and Trettel, Incorporated)

"The Useful Potential of Using Existing Data to Uniquely Identify Predictable  
Wind Events and Regimes - Part II"

C. Notis  
(Freese-Notis Weather, Inc.)

"Atmospheric Turbulence Parameters for Modeling Wind Turbine Dynamics"

W. E. Holley  
R. W. Thresher  
(Oregon State University)

"Inherent Uncertainties in Meteorological Parameters for Wind Turbine Design"

J. C. Doran  
(Pacific Northwest Laboratory)

"Potential Errors in Using One Anemometer to Characterize the Wind Power  
Over an Entire Rotor Disk"

R. L. Simon  
(Pacific Gas and Electric Company)

WIND AND TURBINE CHARACTERISTICS NEEDED FOR  
INTEGRATION OF WIND TURBINE ARRAYS INTO  
A UTILITY SYSTEM

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East Lansing, Michigan 48824

ABSTRACT

Wind data and wind turbine generator (WTG) performance characteristics are often available in a form inconvenient for use by utility planners and engineers. The steps used by utility planners are summarized and the type of wind and WTG data needed for integration of WTG arrays suggested. These included long-term yearly velocity averages for preliminary site feasibility, hourly velocities on a "wind season" basis for more detailed economic analysis and for reliability studies, worst-case velocity profiles for gusts, and various minute-to-hourly velocity profiles for estimating the effect of longer-term wind fluctuations on utility operations.

Wind turbine data needed includes electrical properties of the generator, startup and shutdown characteristics, protection characteristics, pitch control response and control strategy, and electro-mechanical model for stability analysis.

INTRODUCTION

Although a large number of reports and papers have been published on the integration of wind turbine generators (WTG) into electric utility systems [1,2,3,4] utility planners and engineers still have some difficulty assembling wind and WTG data in a form applicable to their planning and analysis methods. The situation is improving and it is the purpose of this brief paper to summarize utility needs so that wind data and WTG performance characteristics can be presented to facilitate utility application of WTG's in a manner consistent with the evaluation of conventional and other alternative sources of electric power.

UTILITY EVALUATION PROCEDURES

It would be presumptuous of any author to claim to describe/generation evaluation procedures in a complete utility generic way. Nevertheless, many observers could agree that the following steps are encountered by most utilities who become involved in wind integration.

- Sensitivity of utility management, public or regulatory agencies of need to evaluate wind as an alternative energy resource.

- Determination whether the technology and projected production of WTG's are adequately defined and characterized for preliminary evaluation. At this point one can differentiate between smaller customer owned WTG's (under 100 kW) and larger utility-owned machines (more than 100 kW). The smaller customer-owned machines are primarily a problem for distribution personnel and are addressed elsewhere [5,6]. The paper concentrates on larger utility-owned WTG's in arrays.
- Determine rough WTG size and siting parameters. Are feasible sites available in the service territory? What wind data is available for these sites?
- Estimate average annual energy (in kWh) available from several projected commercial WTG's at potential sites. Determine penetration levels (wind capacity as percentage of total capacity). Calculate rough economic cost of energy on fuel displacement basis.
- Use hourly wind data for potential sites and a simplified production costing program to determine generation mix with wind and an improved estimate of generation costs for the wind seasons present at the various potential sites.
- Estimate collection costs for interconnecting and controlling the array, transmission costs to the existing network for reasonable voltage variations and current flows under fault conditions, and protection (relaying) configuration and costs. Load flow, stability, and short circuit programs likely used in this step where effects of gusts, short circuits, and synchronizing are analyzed.
- Calculate or simulate the operation of arrays under various wind fluctuation conditions to determine effect of WTG's on area control error, frequency, and thus dispatch. Investigation of protection of the WTG's themselves, noise, and extreme weather conditions may be done at this point.

#### WIND DATA NEEDED

The steps in the previous section require various types of information about the wind regime in the potential array site areas.

#### For Rough Economic Estimate

Yearly average or distribution at potential sites. If the yearly average is not an adequate estimator for certain WTG's, the manufacturer should specify what data is needed for an estimate of annual energy.

### For Simplified Production Cost

Either data or a probabilistic model to generate hourly wind velocity samples characteristic of the potential sites to yield monthly or seasonal wind velocity behavior typical of the site. Either minimum WTG spacing or corrections for WTG interactions which reduce energy production should be specified. The production cost program will indicate reliability of power production as well as cost along with an appropriate generation mix for the array and site configuration chosen.

### For Collection, Protection and Stability

Here the analyst needs peak expected wind velocity, time profile of gusts, and interarray wind behavior.

### For Array Operation

Trends and oscillations in wind velocity over the array on a 20 to 40 minute time interval are needed [7]. This is to determine area control error, frequency of system, and demands on conventional regulating units. Generator unit commitment and system dispatch usually requires adjustment if wind penetration is over several percent.

The key point is that the utility system is not affected directly by the wind velocity (unless it is of destructive force) but by the electrical behavior of the WTG array. The utility will be concerned about excessive array power output fluctuations and above excessive var and voltage fluctuations.

This list of needs suggest the following wind data set as desirable and useful:

- Yearly long-term average velocities or distributions for rough estimation of yearly array energy output.
- Hourly wind velocity model across a potential site for refined economic feasibility and reliability estimates. This data should indicate the range expected over high and low wind years.
- Expected worst-case (extreme) velocity profiles for gusts, as caused by storms and fast frontal passages over a time frame of seconds to a few minutes. These profiles should included space variables to describe velocity over potential array sites. Note that wind direction primarily affects array configuration and may have operating affects if wind direction changes rapidly.
- Wind velocity profiles from a few minutes to an hour to represent effects of array power output on the utility system operating variables.

## WTG SPECIFICATIONS NEEDED

Since the WTG design and controls, as well as array configuration, determine the transfer relation between wind velocity and power output, WTG specifications should include:

- Electrical parameters specifying characteristics of the generator for short circuits, load flow and stability studies.
- Startup and shutdown characteristics as a function of present and past wind velocity for operating effects determination and for resynchronization studies.
- Protection characteristics of the WTG itself, eg: trip settings for overcurrent, phase angle, voltage and frequency relays.
- Characteristics of the blade pitch controller, especially at and below rated power.
- Electro-mechanical model for stability and synchronizing studies.

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## QUESTIONS AND ANSWERS

G. L. Park

From: A. Swift, Jr.

Q: Do utilities prefer utility-owned or consumer-owned wind generators?

A: *That is a function of the utility and specifically apparently the size of the utility grid and the location of the proposed wind generator with respect to the utilities lines. Large utilities don't mind privately-owned wind generators, small ones are more inclined to object.*

From: G. G. Biro

Q: Do you have any difficulty getting wind turbine response times for various startup and shutdown conditions?

A: *No, for Boeing but it still took many hours to get it straight.*

Q: How do the WECS manufacturers supply the station energy need for operations, which is needed for evaluation of total net energy production?

A: *They state peak power consumption for auxiliaries.*

LONG-TERM ENERGY CAPTURE AND THE EFFECTS OF  
OPTIMIZING WIND TURBINE OPERATING STRATEGIES

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Richland, Washington 99352

ABSTRACT

One of the major factors driving the evolutionary design of wind turbines is the cost of energy (COE). The COE for electricity produced by any means is based on three primary factors: capital costs plus operating and maintenance (O&M) costs divided by the number of kilowatt hours produced per year. Obviously an increase in production of energy has the positive effect of decreasing the cost of energy produced by a wind turbine.

A research effort has been established to determine the possible methods of increasing energy capture without affecting the turbine design. The emphasis has been on optimizing the wind turbine operating strategy. The operating strategy embodies the startup and shutdown algorithm as well as the algorithm for determining when to yaw (rotate) the axis of the turbine more directly into the wind.

Using data collected at a number of sites, the time-dependent simulation of a MOD-2 wind turbine using various, site-dependent operating strategies has provided evidence that site-specific fine tuning can produce significant increases in long-term energy capture as well as reduce the number of start-stop cycles and yawing maneuvers, which may result in reduced fatigue and subsequent maintenance.

INTRODUCTION

The economic viability of wind power in the current and future market is a multifaceted question and may be a function of the intended use by a utility and the utilities' own-operating strategy. These factors aside, the optimization of a large wind turbines' computer controlled operating strategy could produce the desirable effect of increased energy production and decreased wear on the machine. At a recent Wind

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830 by Battelle Memorial Institute.

Turbine Designers Workshop held in Seattle, several engineers from industry emphasized that the primary factor to be reconciled with in designing a wind turbine is cost of electricity (COE). This cost is estimated on the basis of interest rate on money borrowed, the capital equipment cost, the annual operation and maintenance cost and the energy produced.

Current estimates of the cost of capital (or actually cost of borrowing money) to an investor-owned utility have risen to 20 to 22%. The O&M costs for large wind turbines, such as a MOD-2, are estimated to be between \$20 and 25 thousand per year. Using the hundredth-unit cost for a MOD-2 wind turbine and an energy capture of 6 GWh per year, we can calculate the cost of electricity as:

$$\text{C.O.E.} = \frac{0.20 (\$2.0 \times 10^6) + \$25,000}{6 \times 10^6 \text{ kWh}} = \$0.07 \text{ kWh}$$

It is obvious from the form of the equation that any percentage increase in energy capture results in an equal percentage decrease in COE.

The inherent decrease in COE became the motivation for this and several ancillary studies to determine ways to optimize wind turbine operating strategies as well as providing guidance to candidate site wind measurement strategies and recognition of the scales of atmospheric motion which affect wind turbine operations.

## BACKGROUND

Research in wind energy seems to have been focused on two distinct yet different scales or areas: wind resource assessment and wind turbine dynamics. The end-user, in almost all cases a utility, has requirements and standards which are in a totally different time frame. The areas which have received emphasis can easily be equated to scales of atmospheric motion illustrated in Figure 1.

Resource assessments are typically based on a monthly, seasonal, and/or annual bases. This corresponds to space scales of thousands of kilometers and would fall into the lower left hand portion of Figure 1. Machine dynamics or loads on the other hand, are most concerned with second to minute and at most, hourly average time scales. The time frame between a few seconds and a month or slightly less are of major concern to an electricity generating agent. Since a number of major and frequently occurring atmospheric phenomena occur in that "window" and could impact a utility, a model, or more appropriate, a simulation of the current generation of large wind turbine, the MOD-2, was developed.

## THE MODEL

First reported a year ago [1] the original model has evolved but only in terms of output products. Figure 2 is a narrative flow diagram of

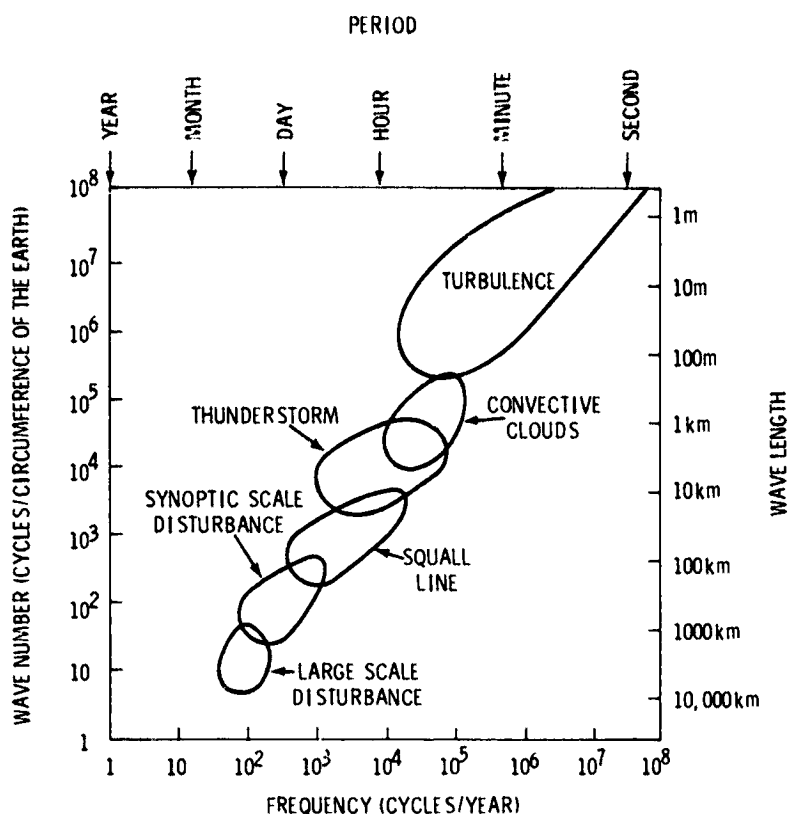


FIGURE 1. SCALES OF SOME COMMON ATMOSPHERIC PHENOMENA IN TERMS OF FREQUENCY, PERIOD, WAVELENGTH AND WAVE NUMBER (MODIFIED FROM MEYER [2])

the MOD-2 simulation. The attributes of this simulation are that it takes into account all of the losses incurred by the MOD-2 in its start up, yawing and shut down strategy as well as seasonal atmospheric density depending on the site under investigation and losses due to wind being off-axis. Currently the program is set up to run using the DOE 2 min candidate site data since they consist of a variety of high wind resource sites with continuous data for as much as 2 to 2-1/2 yr. Though 2 min instantaneous data may not be an accurate representation of the true 2 min average wind speed and therefore may give somewhat biased short-term statistics, the assumption that the instantaneous value is representative of the 2 min average wind speed will not cause any significant effects in the long run.

The MOD-2 simulation model is initialized in an interactive mode. Since all the candidate site data are in an existing file, the site and period of interest are input as well as variations one may want to impose such as changing the maximum directional (yaw) error or motoring the generator. Figure 3 is a presentation of a typical interactive session. Upon execution the first data sample is read in and some quality checks are made to assure that the data is reasonable. Assuming the data is good and the wind speed  $\geq 6.26 \text{ ms}^{-1}$ , the program determines the length of time over which the wind speed must be integrated before a "startup" can proceed. The time required is a function of the

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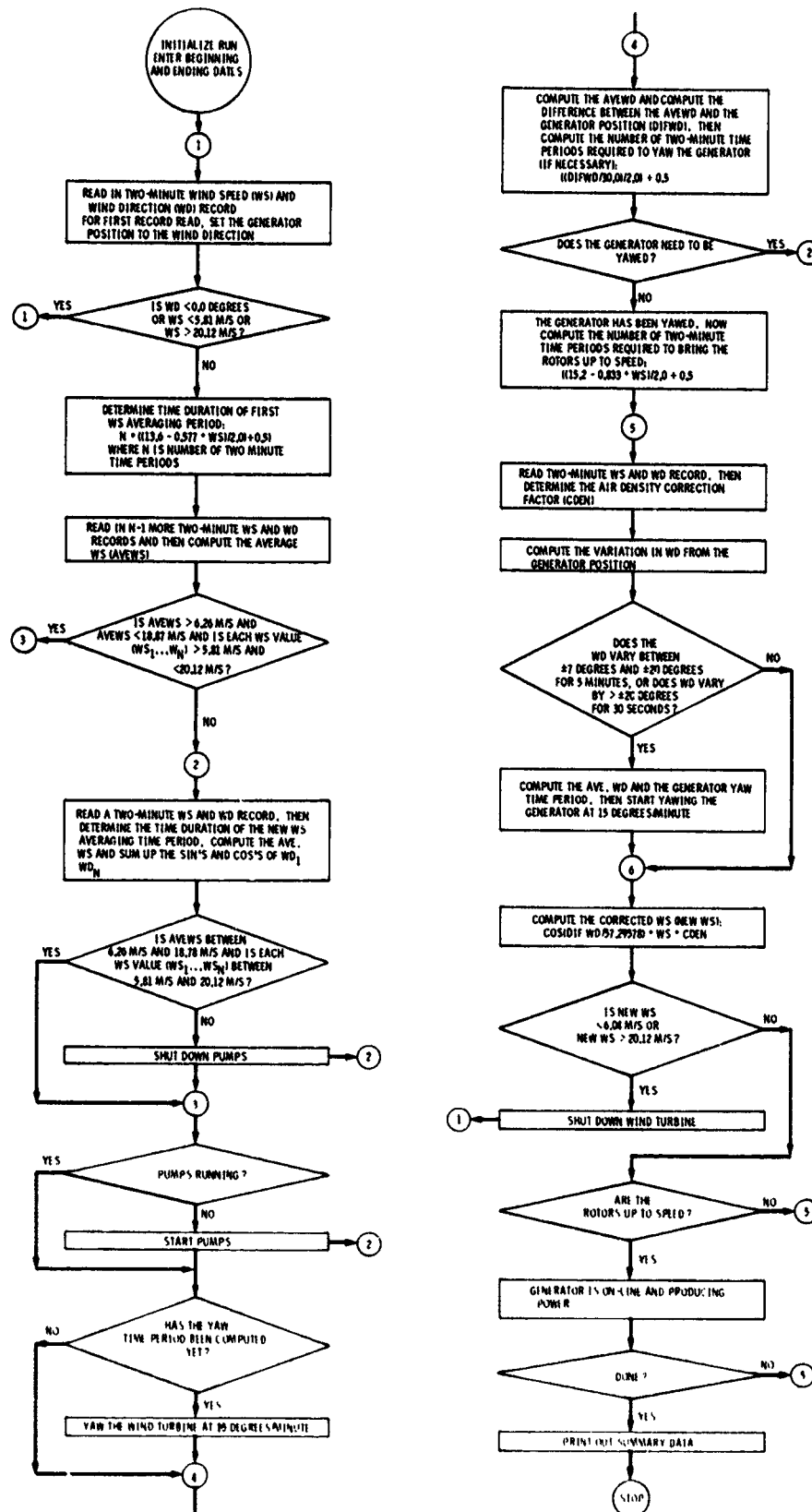


FIGURE 2. FLOW DIAGRAM OF THE MOD-2 SIMULATION MODEL

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```
run mod2sim?
INPUT FILE?... wadat.090
IS THIS A MVP FILE? (1=YES,0=NO) 1
OUTPUT FILE?... wa09.kuh
PLOT FILE?... wa09.plt
HISTOGRAM FILE?... wa09.hst
BEGINNING JULIAN DATE?... 245
ENDING JULIAN DATE?... 274
IS THE STARTING DATE > ENDING DATE? (1=YES, 0=NO) 0
FULL REPORT? (1=YES,0=NO) 1
INCLUDING OFF-LINE DATA? (1=YES,0=NO) 1
MOTOR THE GENERATOR? (1=YES,0=NO) 1
FOR HOW MANY 2 MINUTE TIME PERIODS?...2
STANDARD MOD2 YAW DISPERSION IS 20 DEGREES
WHAT SIZE YAW DISPERSION DO YOU WANT?... 20
```

FIGURE 3. A TYPICAL CRT DISPLAY OF THE INTERACTIVE SESSION TO RUN THE MOD-2 SIMULATION. THE CAPITALIZED WORDS ARE THE COMPUTER GENERATED QUESTIONS, THE SMALL LETTERS ARE THE INPUTS.

wind speed and if the wind speed increases sufficiently during the integration period, that period is shortened commensurately. If the average speed is inadequate or "limit" criteria have been exceeded then the wind speed integration is reinitialized. If on the other hand all criteria have been met for a startup the program tells the "turbine" to start its hydraulic pumps. This operation on a real MOD-2 takes 2 min between command and the hydraulic system being ready to operate. The next step is to yaw the turbine into the wind ( $\pm 5^\circ$ ) except for the very first startup at which time the turbine is assumed perfectly aligned with the first wind direction. In reality a MOD-2 wind turbine can be yawed  $15^\circ \text{ min}^{-1}$  and therefore if the yaw error is less than  $30^\circ$  the model simply assumes that the yaw maneuver has occurred between successive data points and prints out such a message. Once any yaw error has been accounted for and the hypothetical "brake" released, the model computes the length of time required for the turbine blade to come up to synchronous speed and begin generating electricity. Once on line the model will continue to simulate all the yaw maneuvers as well as the power out for as long as  $6.04 \text{ ms}^{-1} < \text{wind speed} < 20.12 \text{ ms}^{-1}$ .

Figure 4 shows the characteristic curve of MOD-2 power out versus wind speed. In Figure 4 it appears there are two cut-in speeds. In fact, one is the cut-in speed (14 mph) while the lower speed (13.5 mph) is actually the low speed cut-out. The MOD-2 is unique in that it is the first multimegawatt, upwind turbine thereby casting the nacelle mounted control anemometers in a "wind shadow" once the turbine blades begin to rotate. Because of this, once on line, the turbine becomes its own control anemometer. Low speed shut down occurs not when a minimum apparent wind speed is reached but rather when the turbine output power reaches  $< 125 \text{ kW}$ . To simulate the MOD-2 the wind data are used to calculate power out by the polynomial:

$$P_{\text{kW}} = -541.0 - 93.5 V + 39.2 V^2 - 0.909 V^3$$

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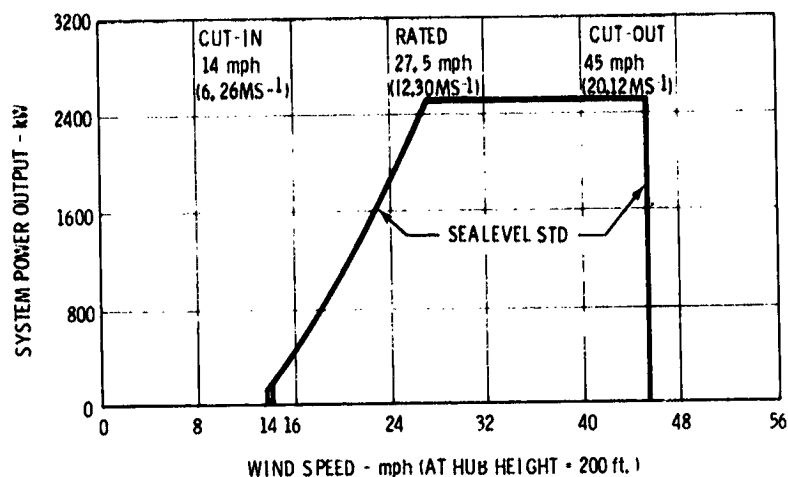


FIGURE 4. OUTPUT POWER CHARACTERISTICS VERSUS WIND SPEED FOR A MOD-2

to the limit  $P_{kW} = 2500$ . Above  $12.3 \text{ ms}^{-1}$ , rated on the MOD-2, the simulation maintains constant power up to a wind speed of  $20.12 \text{ ms}^{-1}$  above which the turbine is cut off line and brought to a stop. On a high speed cut off, the wind speed average must be below approximately  $18.3 \text{ ms}^{-1}$  for at least 4 min before the turbine is brought back on line. During those periods when the simulated MOD-2 is online and generating the model is keeping track of the wind direction and the actual yaw angle of the wind turbine. If the average yaw error is between  $\pm 7^\circ$  and  $\pm 20^\circ$  the turbine will be yawed directly into the wind after 5 min. If the error exceeds  $\pm 20^\circ$  for 30 s a correction is applied immediately. In these cases 6 min and 2 min are used respectively due to the data base. Though this appears to introduce some error the time required for the wind turbine to be yawed (at  $15^\circ \text{ min}^{-1}$ ) uses up the majority of the time difference in either case. Also during periods when the simulated turbine is online a cosine correction for the yaw error is applied to the wind speed before power out is computed.

Atmospheric density effects are applied seasonally. These were calculated from NASA Standard Atmosphere data. The density correction is only applied to the power producing wind but not to the wind speed data prior to power production. Since both cup and propeller anemometers are zero-balance devices they have been shown to be essentially unaffected by density at least up to altitudes well above any anticipated turbine site. Therefore the startup strategy would be unaffected unless it were intentionally modified but the turbine output would be reduced as a function of density.

#### APPLICATION OF THE MODEL

During the evolutionary development of the MOD-2 simulation model it was applied to diverse candidate site data. Output products include (if desired) a hard copy minute-by-minute account of the status of the MOD-2 for each datum. Analysis and interpretation of such a product led to the concept of computer optimization of large wind turbine



operating strategies. As described in the preceeding section the MOD-2 simulated operating strategy accounts for the following:

Cut-in - the time between initialization and power generation is in three steps: 1) integrating the wind speed data before turning on the hydraulic pumps; 2) turning on the pumps and yawing the machine into the wind and 3) determining the length of time required for the rotor blade to reach synchronous speed.

Yaw maneuvers - also a function of time, handles the modelled positioning of the turbine with respect to the wind direction and reduces the power out by reducing the apparent wind speed by the cosine of the error.

Turbine shutdown - occurs when power out drops below 125 kW or the wind speed corrected for density exceeds  $20.12 \text{ ms}^{-1}$ .

Obviously no modification of the design of a MOD-2 could be anticipated or tolerated in modifying the operating strategy. The initial step was to run the model for a complete year at a number of sites. Five sites were chosen on the basis of different topography and/or somewhat unique wind regimes. The sites chosen were, Holyoke, MA, Ludington, MI, Kingsley Dam, NB, Clayton, NM, and San Geronio Pass, CA. Results of three of these simulations are shown in Figure 5. Subsequently single months from each site characterized by the smallest amount of missing data, were picked for further testing.

Investigation of the distribution of yaw errors led the authors to believe that reducing or increasing the yaw error limits may serve to increase energy production without prohibitive increases in the number of yaw maneuvers. The simulation was once again run on each site for a selected month varying the allowable maximum yaw error from the base  $20^\circ$  to  $10^\circ$ ,  $15^\circ$ , and  $25^\circ$ . The results are tabulated in Table 1, Section A.

The second set of modifications involved the startup strategy. The standard (base case) algorithm for determining the wind speed integration period is a function of wind speed varying linearly from 10 min at  $6.26 \text{ ms}^{-1}$  to 2 min at  $20.12 \text{ ms}^{-1}$ . This was modified such that the 2 min upper limit occurred at rated wind speed,  $12.3 \text{ ms}^{-1}$ . Further, besides running the model with the original  $20^\circ$  yaw error limit a second set of runs with a  $10^\circ$  yaw error limit was run. Results of these tests are given in Table 1, Section B.

The third sequence of tests had a dual purpose. Start/stop cycles and yaw maneuvers, however necessary, are believed to be large contributors to fatigue and maintenance. In an attempt to reduce false starts and possibly increase energy production simultaneously, the wind speed integration period at cut-in speeds was increased to 12-min. Further, both  $10^\circ$  and  $20^\circ$  upper yaw error limit cases were run for comparison. The results can be seen in Table 1, Section C.

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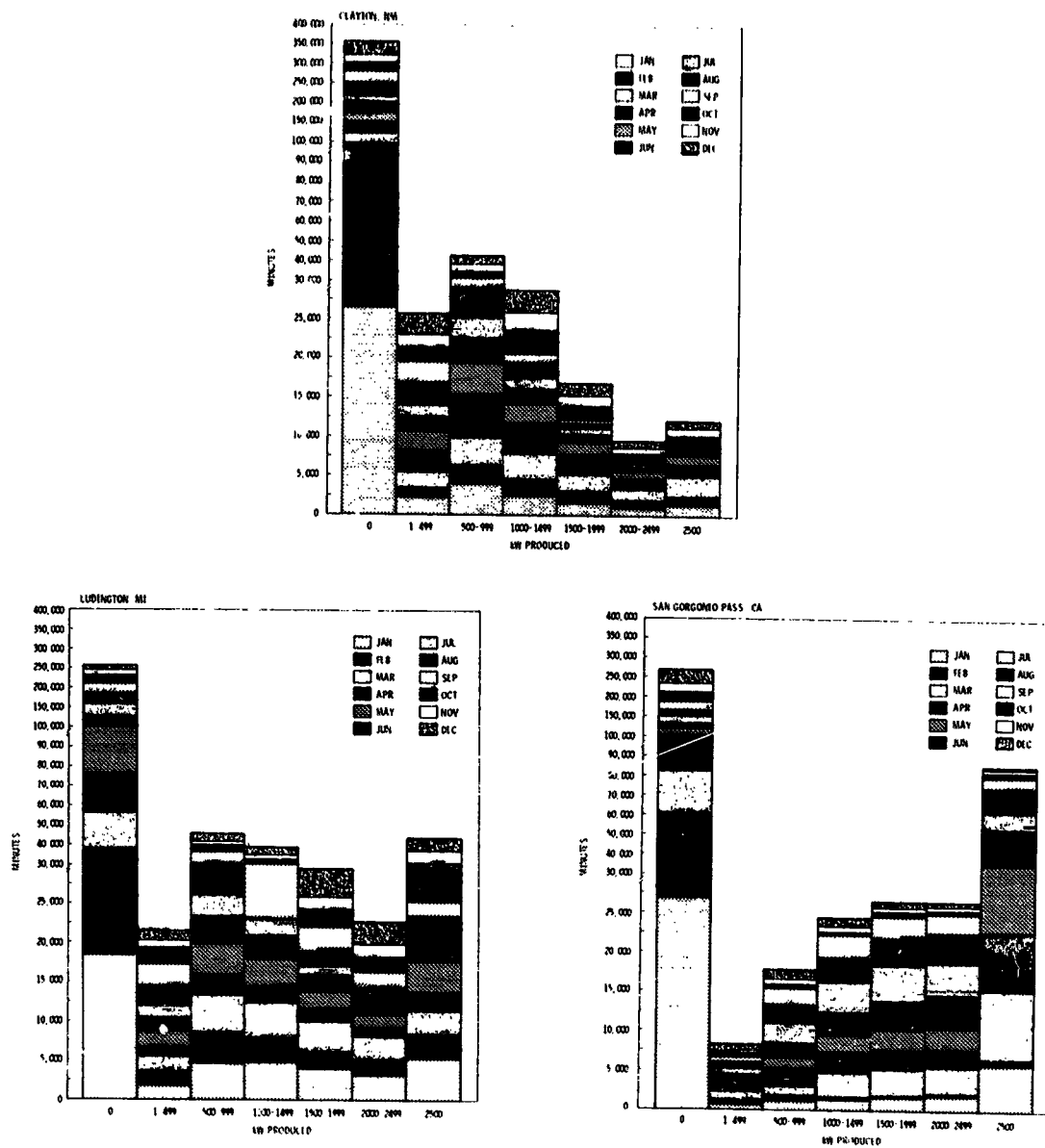


FIGURE 5. CUMULATIVE MONTHLY POWER PRODUCTION HISTOGRAM FOR 1 YR AT THREE SITES. NOTE: SCALE CHANGES AT 30,000 AND 100,000 MIN.

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TABLE 1. MOD-2 SIMULATION RESULTS

	A				B		C		D	
	10°	15°	20°	25°	10°	20°	10°	20°	Free-Wheeling	Motoring
<u>MA Jan</u>										
kWh	351088	355611	355203	355708	355708	358688	354756	357791	388090	379464
Start/Stops	114	108	109	110	121	117	119	114	44	43
# Yaws	2091	1212	768	586	2149	795	2117	794	860	895
False Starts	47	43	43	41	44	42	38	35	25	15
<u>NM Dec</u>										
kWh	219688	219590	220114	219746	222218	222561	219783	220300	231461	238182
Start/Stops	181	182	180	183	193	189	179	180	135	92
# Yaws	1091	530	343	303	1154	355	1106	340	379	461
False Starts	346	348	349	346	364	368	314	311	322	258
<u>MI Jul</u>										
kWh	145499	146060	146193	145707	147806	148159	145414	146132	161088	163187
Start/Stops	130	129	129	131	136	136	123	122	86	62
# Yaws	714	389	260	203	753	253	703	249	302	359
False Starts	121	120	119	119	119	115	111	109	97	84
<u>NB Jan</u>										
kWh	311459	311382	311078	311996	315471	316033	311260	310857	356731	337311
Start/Stops	158	167	169	168	179	178	167	168	111	84
# Yaws	1454	644	409	365	1470	414	1439	407	516	565
False Starts	123	124	123	121	130	128	110	111	94	74
<u>CA Nov</u>										
kWh	140949	141315	141067	141044	142769	142756	142655	142774	158185	145422
Start/Stops	40	40	40	40	43	43	45	45	27	26
# Yaws	566	271	155	131	575	157	564	157	172	200
False Starts	50	49	49	49	61	62	43	42	46	45

A - Results from varying the maximum yaw error parameter (20° is the standard design value)

B - Results of reducing the startup integration period

C - Results from increasing the low wind speed startup time

D - Results with free-wheeling and "motoring" allowed (both cases at 20°)

The last two attempts to modify the MOD-2 operating strategy are of a somewhat speculative nature and, though quite different in philosophy are quite similar in nature. Both cases were run with only the 20° maximum yaw error (base case). The differences can be identified by equating the modifications to a passive and an active method of accomplishing the same goal. In the passive case the low speed cut-off ( $6.04 \text{ ms}^{-1}$ ) was invoked by a two-sample (4-min) average rather than a single datum while the active method utilized the synchronous generator as a motor to keep the rotor speed up. While the passive case was equivalent to allowing the turbine to free-wheel for short periods, the active case used power equivalent to a 200-hp electric motor (P.F. = 0.8) to keep rotor speed up. In this case the power consumed in the "motoring" mode was subtracted from the accumulated power produced. In the motoring case the turbine was allowed to motor for up to 4-min at every shutdown. If in fact the turbine experienced positive torque-winds  $\geq 6.26 \text{ ms}^{-1}$ --the motoring was immediately cut-off. While it is known that a MOD-2 could be operated in the motoring mode, the passive or free-wheeling mode may in fact add unnecessary stresses to the turbine and support structure.

Results from the five sites for both modes of operation are listed in Table 1, Section D.

## DISCUSSION

During the course of this study a number of unexpected results surfaced which, though somewhat outside the scope of this report, are worth reporting. Though the MOD-2 simulation model is undoubtedly subject to the vagaries of the 2 min instantaneous data, the only minor effect is likely to be in the number of low speed start/stop cycles. Otherwise for periods of the order of less than a week and longer the effects of the data should be minimized if distinguishable at all. As mentioned earlier the first step in this study after development of the computer model was to pick some sites and run a base case "bench-mark" against which all variations of the operating strategy could be compared. The result of each site's run included annual cumulative total kilowatt hours produced. These results did not account for missing data. Assuming the missing data over the period of 1 yr were scattered randomly throughout the whole sample the resulting total was normalized by the ratio of time the machine was "on-line" versus "off-line" (a percentage) multiplied by the total time missing multiplied by the site average power and adding that to the power produced. Figure 6, the power duration curves for the five sites, also gives the resulting GWh produced using the site hourly average wind speeds. The annual power production for these sites resulting from the annual operating strategy simulation are shown in Table 2.

The dot on each power duration curve is the annual average power for the site. Figure 7 shows the normalized wind frequency distribution and the site annual average wind speed and average power derived from the hourly average wind speed. Table 3 gives these values and the values calculated from the MOD-2 simulation model.

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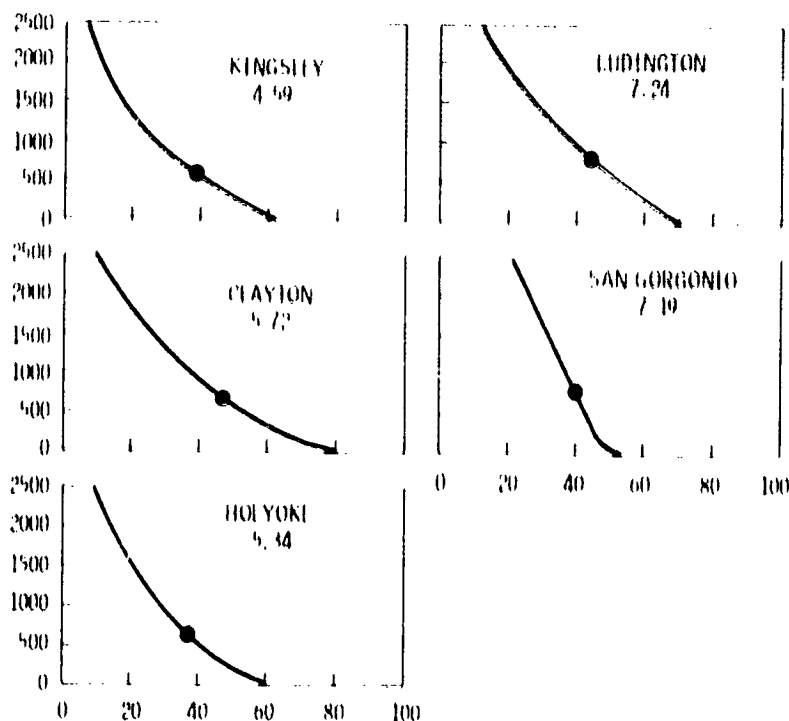


FIGURE 6. HOURLY DISTRIBUTION OF POWER OUT OF A MOD-2 BASED ON DATA FROM 45.7 M HEIGHT. THE NUMBER BELOW THE SITE NAME IS THE NUMBER OF GWh ( $10^6$  kWh) OF ENERGY PRODUCTION ANNUALLY. THE ABSCISSA IS THE PERCENT TIME THE TURBINE IS EQUAL TO OR GREATER THAN THE POWER LEVEL ON THE ORDINATE.

TABLE 2. ANNUAL MOD-2 POWER PRODUCTION COMPUTED TWO WAYS

Site	Hourly Average (GWH)	Operating Strategy Simulation (GWH)	Difference (%)
Kingsley, NB	4.59	2.93	-36
Clayton, NM	5.72	2.87	-51
Holyoke, MA	5.34	2.90	-46
Ludington, MI	7.24	6.27	-14
San Geronio, CA	7.19	7.60	+ 6

The interesting point evidenced in Figures 6 and 7 and Tables 2 and 3 is that the resulting differences appear to be uncorrelated with topography, altitude or geographic location. The results obtained by modifying the operating strategies may offer a clue. Examining Table 1 on a site by site basis one notes that at the Holyoke, MA site the greatest gain in power (with the exception of the free-wheeling and motoring cases) comes from the shorter integration time at startup (Section B). Though there is a concomitant increase in number of yaws, that increase is tolerably small. The increase in power leads one to believe that the characteristic wind rises in velocity fairly rapidly from less than

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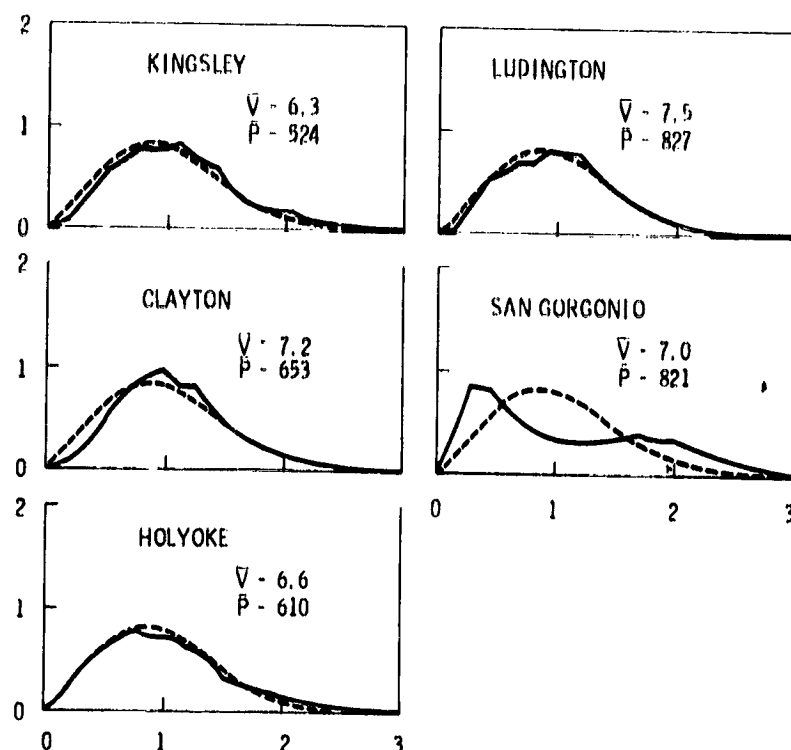


FIGURE 7. NORMALIZED FREQUENCY DISTRIBUTIONS OF HOURLY WIND SPEED DATA (SOLID LINE) AND THE NASA MODIFIED WEIBULL DISTRIBUTION BASED ON THE ANNUAL MEAN WIND SPEED (DASHED LINE).  $\bar{V}$  IS THE ANNUAL MEAN WIND SPEED ( $\text{ms}^{-1}$ ) AND  $\bar{P}$  IS THE AVERAGE ANNUAL WIND POWER(kW).

TABLE 3. AVERAGE POWER FROM A MOD-2 FOR FIVE SITES CALCULATED TWO WAYS

Site	Hourly Average Wind Speed (kW)	Simulation Average (kW)	Difference (%)
Kingsley, NB	524	334	-36
Clayton, NB	653	319	-51
Holyoke, MA	610	331	-46
Ludington, MI	827	707	-14
San Geronio, CA	821	868	+ 6

cut-in but judging from the lower power produced with a  $10^\circ$  maximum yaw error further leads to the belief that the directional variability is quite high. Assuming that is true the machine apparently "chases" the wind while concurrently losing energy. The increase in power shown by free-wheeling over motoring further indicates the wind speed must be in

the lower portion of the power curve dipping frequently below cut-out and then right back up. Therefore the power consumed in motoring is not unuseful but costly. The second site studied, Clayton, NM exhibits some similar attributes to Holyoke, MA as shown in Table 1, Section B. One startling difference is in the apparent number of false starts i.e., the number of times the machine would go all the way through the startup procedure according to the operating strategy but shutdown before any power was produced. Slowing down the low wind speed startup (Table 1, Section C) served to reduce the number of false starts by 11% without however, any appreciable increase in power production. The difference in production between motoring and free-wheeling shows that lulls in wind speed at Clayton are apparently of the order of 4-5 min which is adequate to cause shutdown in the free-wheeling mode but is picked up by motoring and thereby put back on-line with minimum loss. Though this may indicate the size eddies characteristic at Clayton, insufficient investigation into conditions when such eddies occur has been accomplished to call these eddies characteristics. More stringent interpretation of the example results presented here will be found in several forthcoming PNL reports.

#### SUMMARY AND CONCLUSION

In the limited space available in this forum it is quite difficult to paint a very exact, interpretative picture of the design, development, utilization and results of the use of something like the computer model of the MOD-2 wind turbine. The model was developed in a logical manner and as it was put to more and more use more and more output products evolved. Most of these products have been left out of this report. As of the present our investigation has centered on simple power production and the effects of changes to the production as well as those attributes which may affect the structural dynamics of such a turbine. These results are found in Table 1, Sections B, C, and D and example interpretations found in the Discussion section. The results presented here clearly indicate that site specific, relatively short-term wind characteristics do have an effect on energy production from a MOD-2 wind turbine and the operating strategy can be refined to increase power production without intolerable increases in stress producing maneuvers. Further, though unreported here studies of the modeled operations of a MOD-2 are pointing out the differences and similarities in the larger (synoptic) scale effects on wind characteristics at specific sites such that in the future, armed with a proper understanding of large wind turbine operating characteristics the scientific community can better evaluate expected performance on the basis of hourly data.

#### ACKNOWLEDGMENTS

This work was supported by the Department of Energy under contract DE-AC06-76RL0 1830.

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## QUESTIONS AND ANSWERS

A. H. Miller

From: A. Jagtiani

Q: What's the cost per kWh of MOD-2?

A: *Ignoring the costs of site preparation and the legal and institutional issues and based on the 100<sup>th</sup> unit cost of \$2 million, at the current rate investor owned utilities pay to borrow money assuming 6 GWh generation per year the cost of electricity is about \$0.07 kWh.*

Q: What percent of time in a year was the wind turbine operating at rated kW. Also, what's the overall efficiency of the machine?

A: *The percent time a wind turbine is at rated power is site dependent but for the sites studied extensively here the typical is only 2 or 3% of the time based on 2 min by 2 min time periods.*

*The overall efficiency I look at is called plant factor which is the ratio of what the integrated wind speed indicates should be producible to what is actually produced. The values are typically of the order of 0.3 or 30%.*

Q: What's the minimum centerline to centerline distance in all directions required for MOD-2, so they will not interfere with each other?

A: *At this point no one knows the minimum centerline to centerline distance required for noninterference. The MOD-2 wind turbines are set up in an array to study wake effects with the three machines set up along lines of the prevailing winds 5, 7 and 10 diameters apart. I suggest you contact Pat Finnigan of NASA Lewis as he has been doing some calculations on the subject.*

Q: I am replacing a 1300 MW unit. How many MOD-2s will be required, how much land will be required and what confidence interval will there be that we will have power at all times?

A: *1300 MW of installed capacity in MOD-2s would amount to 520 turbines, if WTS-4s were used the number would be 325. The amount of land required is a function of the arrangement and is hard to specify. It is conceivable that the amount of land required for exclusive use of an individual large turbine is less than an acre, however, access roads and the likes must be added in.*

*My confidence that there will be power out of wind turbines at all times is 100% that there absolutely will not be power at all times. When one can count on it is quite site and geographic locale specific.*

INTEGRATION OF WIND TURBINE GENERATION (WTG)  
INTO UTILITY GENERATING SYSTEMS

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Extensive progress has been made in the 1970's along the path of integrating wind turbine (WT) generators into utility systems. Analytical tools have been developed for determining the impact of wind generation on utility cost of generation and generation planning. However, little has been done either in determining the sensitivity of study results to wind power modelling techniques nor in developing methods for determining how WT generation would effect the operation of a utility in meeting its daily load requirements. This abstract describes the analysis performed by JBF Scientific Corporation, for the Pacific Northwest Laboratory, in order to examine the sensitivity of a utility's cost of generation to its ability to accurately forecast wind speeds. The study also examined the sensitivity of utility cost of generation to both wind speed sampling frequency and wind turbine performance model. The objective of the study was to determine the information that a utility would require in order to economically integrate WT generation into the operation of its system.

The study used two-minute wind speed data, measured in 1979 at the DOE meteorological tower located in the San Geronio Pass, California, for the available wind resource. The wind turbine simulated on the study was the MOD-2 built by the Boeing Engineering Corporation. Four different simulation methods were used in calculating the expected performance of MOD-2 wind turbines in the San Geronio wind environment:

1. A time-dependent performance simulation of machine operation that calculates power output from the 2-minute wind data and includes control logic for startup and shutdown, yawing, and system time constants. For each hour, the 2-minute power calculated is integrated to obtain the WTG's average hourly power output.

2. An integrated hourly performance model that calculates machine output every 2 minutes. Hourly power output was calculated by integrating 2-minute power output over each hour.
3. An hourly sampled wind speed performance model that uses the last 2-minute wind speed sample taken every hour to represent the hourly wind speed. This method is similar to that used when using SOLMET wind speed data.
4. An hourly averaged wind speed performance model that uses hourly averaged 2-minute wind speed samples in calculating hourly machine output.

The hourly MOD-2 outputs defined by the four techniques were used as load modifiers in defining the net load that must be serviced by conventional utility generating sources. On this study net loads were calculated for the projected 1995 Los Angeles Department of Water and Power (LADWP) generating system assuming a 10 percent WTG penetration. These loads were then supplied to a production cost simulation to estimate LADWP's 1995 annual cost of generation. The results were then used in establishing the sensitivity of LADWP's annual production costs and WTG value to the particular technique used in calculating hourly wind turbine generation.

The study also examined the impact wind forecasting accuracy would have on LADWP operation and costs. The objective of this analysis was to establish the sensitivity of LADWP production costs to wind speed forecasting accuracy in an effort to define realistic goals for wind speed forecasters.

The following results were obtained from the analysis performed on this study. Caution must be exercised in generalizing these results since they were obtained by analyzing a single utility under very specific assumptions.

- Using three different non-time-dependent methods for calculating hourly WTG performance resulted in less than a 3 percent difference in the calculated MOD-2 capacity factor. Similarly, WTG life-cycle value calculated also varied by less than 3 percent regardless of the non-time-dependent model used.
- Averaging 2-minute wind speeds each hour does not appreciably (less than 3 percent) change MOD-2 capacity factor, single-year production cost savings, or life-cycle value from that calculated using wind speed samples taken once every hour when WTG power is calculated using a performance envelope.

- Modeling machine performance with a time-dependent simulation and using 2-minute wind speed data does appreciably change the MOD-2 capacity factor, production cost savings, and life-cycle savings from those calculated using a static performance model. Using this simulation decreased MOD-2 performance by approximately 13 percent. This resulted from a combination of increased machine downtime and a decrease in the time the WTG is computed to be operating at rated capacity.
- The ability of LADWP to accurately forecast wind speeds (WTG power) can increase LADWP's operating savings by as much as 20 percent.
- The ability of LADWP to accurately forecast wind speeds (WTG power) can decrease its dependency on swing fuels such as oil.

## QUESTIONS AND ANSWERS

M. K. Goldenblatt

From: R. Barton

Q: How much of the 10-13% difference between the 2 min and 1 hr data input types for wind is directly related to poor characterization of high wind duration with smoothed characteristics? (I think I saw  $\approx 200$  hr at rated for the time dependent and integrated hourly versus  $\approx 1700$  hr for sampled/averaged hourly).

A: *We did not "characterize" any wind. We used actual 2 min wind data from the meteorological tower for all the models. Only the simulation modeled the effects of startup, yawing and shutdown. At San Geronio the variability of the wind over 1 hr may not allow the machine, represented here by the time dependent simulation, to come up on-line at all but the average speed and the static characteristics may indicate rated power.*

From: G. L. Parks

Q: Why not emphasize that 10-13% energy loss via 2 min calculation calls most hourly studies into question?

A: *Without verification by using other sites or different years and other utility parameters I'd rather not generalize and make too much of the 10-13% yet.*

From: M. Iriarte

Q: Wind forecast will definitely reduce operating costs in the consideration of WECS systems, but what confidence is there in the forecast? Historical data only used?

A: *This was a parametric study and no actual forecasting used. It was a study where only perfect or absolutely imperfect forecasts of the real wind were used to determine the effect on LADWP operations.*

From: M. Lotker

Q: What has been NASA's experience with similar time-dependent data analysis on MOD-OA wind turbine?

From: W. Vachon

A: *NASA examined some 1979 data from the Clayton, NM MOD-OA machine. They found that for about 4-6 wk of data, the major reason for lost energy production was due to machine outage induced by blade problems. They did, however, find that about 10-15% of the energy was lost due to startup and shutdown time.*

THE USEFUL POTENTIAL OF USING EXISTING DATA  
TO UNIQUELY IDENTIFY PREDICTABLE WIND  
EVENTS AND REGIMES - PART I

Dennis W. Trettel  
and

J. T. Aquino, T. R. Piazza, L. E. Taylor, D. C. Trask

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Northfield, Illinois 60093

ABSTRACT

Correlations between standard meteorological data and wind power generation potential have been developed. Combined with appropriate wind forecasts, these correlations can be useful to load dispatchers to supplement conventional energy sources. Hourly wind data were analyzed for four sites, each exhibiting a unique physiography. These sites are Amarillo, Texas; Ludington, Michigan; Montauk Point, New York and San Geronio, California. Synoptic weather maps and tables are presented to illustrate various wind 'regimes' at these sites.

INTRODUCTION

Pacific Northwest Laboratory (PNL) undertook a wind forecast verification study using bivariate time-series analyses. As a consequence of that effort, time-series plots of hourly wind speed and direction were generated. Site specific structures in the wind patterns with respect to time were noted. It was recognized that a valuable tool for the forecasting of wind energy could be produced if the observed wind structures could be correlated with synoptic, subsynoptic or mesoscale weather patterns.

A contract was awarded to Murray and Trettel, Incorporated (M/T) to address the potential use of conventional meteorological data to forecast the wind at four potential wind generation sites.

The sites to be investigated were: San Geronio Pass, CA (SAG); Amarillo, TX (AMA); Montauk Point, NY (MTP); and, Ludington, MI (LDM).

## DATA

The data used in this study came from three (3) sources:

Pacific Northwest Laboratory (PNL) furnished hourly averaged wind speed and direction time-series plots by month for the year 1979. They also furnished speed and direction data in tabular form. The hourly data were based upon measurements taken at two (2) minute intervals.

The National Climatic Center in Asheville, NC (NCC) furnished microfilm products, including analyses of surface, 850, 700, 500 mbs and winds aloft. They were NCC series MF489, MF494 and MF915.

Murray and Trettel, Inc. (M/T) had numerous in-house products available including adiabatic diagrams for Green Bay, WI (GRB) and synoptic sectionals of portions of the USA. In addition the M/T files of the Daily Weather Maps Weekly Series were used extensively particularly in the Booz-Allen classifications.

## GENERAL PROCEDURE

Although there was necessarily some variation in the procedure due to the location and topography of the four (4) sites there was a general procedure that was used at all the sites.

### Data Stratification

The data were tabulated from computer printout according to wind speed, hours of duration of certain wind speeds (7, 10 and 15 mps), maximum speed for the day along with direction and time of occurrence.

The data were stratified based on the following reasoning. The critical wind speed chosen was 7 mps (14 knots). This is just above the 6.26 mps that activates the MOD-2 generator. The number of days for each month that had an hourly wind speed equal to or greater than 7 mps was logged. The number of consecutive hours of speeds equal to or greater than 7 mps was also logged. This was further stratified into three types:

Type 1: less than three (3) consecutive hours of wind speeds equal to or greater than 7 mps.

Type 2: 3-7 consecutive hours of wind speeds equal to or greater than 7 mps.

Type 3: 8 or more consecutive hours of wind speeds equal to or greater than 7 mps.

The rationale for this breakdown was based upon M/T experience in working with electric load dispatchers since 1959. Type 1 would not be a long enough period to produce useful generation; Type 3 would be long enough to produce useful generation; Type 2 was considered a marginal situation.

The data are also being analyzed for 10 mps and 15 mps thresholds and will be included in the final report.

#### Booz-Allen (B/A) Classification

Each day of the year was classified as to weather pattern using the B/A classification for both ground level surface and 500 mbs. A copy of these classifications is found in Appendix A.

The B/A scheme was looked at as only a preliminary step. The advantage of the B/A classification is that it gives a quick and easy description of a synoptic map. However, it has the disadvantage that pressure gradients are not directly specified. This is important in studying wind speeds. In addition, the classification is subject to the interpretation of the individual meteorologist. For example B/A Surface 24 is Pretrough, 29 is Postridge; at 500 mbs 9 is Pretrough, 15 is Postridge.

The B/A index was tabulated for each day rather than just certain selected situations. There were two reasons for this: (1) there was interest not only in the occurrence of strong winds but also periods of light, persistent winds when wind turbine operations would be at a minimum, and (2) it was more efficient to accomplish the entire task at one time. This classification was accomplished using the Daily Weather Map Weekly Series for all four sites.

#### 850 MB Wind Data

The 850 mb wind speeds and directions were tabulated for each day and logged along with the data described above. There was some disadvantage to this because of the difference in elevation of the four sites. However, the 850 mb data and other selected levels (UW/US North America-TTAA) come in on the 604 teletype circuit earlier (1255Z) than the complete sounding. Furthermore using this selected level data would enable the meteorologist to make his forecast without waiting for the complete 850 mb chart on the DIFAX circuit (1433Z). This is a difference of almost two hours - a significant time period in load forecasting.

The radiosonde stations used were Amarillo, TX (363); Green Bay, WI (645) and Flint, MI (637) for Ludington, MI (LDM); New York (486) for Montauk Point (MTP); and Vandenberg AFB (393) and Las Vegas, NV (387) for San Geronio, CA (SAG).



### Second Standard Level Wind Data

As the data logging progressed and some preliminary analysis was begun, the difference in elevation of the various sites led to the conclusion that the wind data at the second standard level should be examined. This would overcome the disadvantage of the 850 mb data mentioned above. But it should also be noted that this information is not available until a later time in the form of UJ1 PPBB on the 604 line (starting at 1356Z) and even later on the DIFAX circuit (1549Z).

The same stations were used as indicated with the 850 mb data.

### Pressure Gradient Analysis

The pressure gradients were measured across the selected sites in two ways. The first method simply logged the pressure difference between two representative stations. For example, in the case of San Geronimo the pressure difference between Los Angeles (LAX) and Las Vegas (LAS) was used. This worked very well particularly for the summer months because the changes in the pressure patterns were minor. However, it became apparent that although this method worked well for San Geronimo, it did not work well for Montauk Point. A second method used the synoptic surface maps and measured the pressure gradient across the site for a distance of 150 nautical miles (75 miles on either side). The direction perpendicular to the gradient was also logged. It was felt that the direction of the gradient would be important due to local effects. This method worked better for the other three sites because they were affected by various pressure systems moving across the area.

### SITE 1: MONTAUK POINT, NY (MTP)

#### Data Stratification

The hourly wind data furnished by PNL were analyzed and divided into Types 1, 2 and 3 described above. Particular emphasis was placed upon a speed threshold of 7 mps because of its impact on the MOD-2 wind turbine and load generation. These data are tabulated in Table 1. In 1979 there was a total of 3,436 hours of winds speeds equal to or greater than 7 mps. This represents 41 percent of the possible total hours. The percentages ranged from a maximum of 68 percent in January to a minimum of 18 percent in July. It was not surprising that the cold weather season (Dec-Feb) showed the highest values (average of 65 percent) with the lowest values (average 22 percent) in the warm months (June through September).

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Table 1. STRATIFICATION OF WIND SPEEDS AT  
MONTAUK POINT, NY - 1979 - TYPES 1, 2 AND 3

HOURS					DAYS									
Mon	Avail	>7 mps			Avail	Type 1		Type 2		Type 3		None		Mag
	Data	obs	poss	%	Data	No.	%	No.	%	No.	%	No.	%	
J	652	442	744	68	28	3	11	2	7	23	82	0	0	3
F	672	437	672	65	28	0	0	5	18	21	75	2	7	0
M	744	277	744	37	31	6	19	5	16	14	45	6	19	0
A	720	293	720	41	30	4	13	6	20	15	50	5	17	0
M	744	299	744	40	31	4	13	7	23	17	55	3	10	0
J	720	174	720	24	30	2	7	6	20	7	23	15	50	0
J	427	77	744	18	19	3	16	2	11	4	21	10	53	12
A	744	154	744	21	24	6	25	2	8	8	33	8	33	7
S	720	188	720	26	30	4	13	7	23	9	30	10	33	0
O	744	311	744	42	31	5	16	3	10	19	61	4	13	0
N	720	328	720	46	30	3	10	3	10	17	57	7	23	0
D	744	456	744	61	31	2	6	3	10	23	74	3	10	0
TOT	8351	3436	8760	41	343	42	12	51	15	177	52	73	21	22

Although the total hours of wind speeds strong enough to activate a MOD-2 generator was of interest it was felt that the number of consecutive hours of speeds equal to or greater than 7 mps would be more significant. The data were therefore further stratified into Type 1, 2 and 3 'days' (See Table 1). The Type 3 day (speeds equal to or greater than 7 mps for 8 or more consecutive hours) were of particular interest. The values ranged from an average high of 22 days (77 percent) in the period December through February to an average low of 7 days (27 percent) in the four month period June through September.

This leads to the conclusion that wind speeds at MTP were strong enough to activate a MOD-2 generator an average of 52 percent of the days in 1979 with values ranging from 82 percent in January to 21 percent in July. Wind power could have a significant impact on the cold weather heating load but minimal impact on the summer air conditioning requirements.

#### Booz-Allen (B/A) Classification

The B/A classification was poorly correlated with the Wind Types and was not considered a highly useful tool in this application except in a general way. As discussed earlier this was not too surprising due to the lack of direct consideration of pressure gradients.

An example of a Type 1 day (light winds) occurred on 15 February and is shown in Figures 1 and 2. Note the weak gradient due to the ridge of high pressure (B/A type = 33, post inverted ridge). The 500 mb

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chart shows strong NW flow (B/A type = 14, pre-ridge). These maps are good examples of the need for judgment by the forecaster. The B/A surface type could have been 33, 34 or 35; the 500 mb could have been 10 or 14.

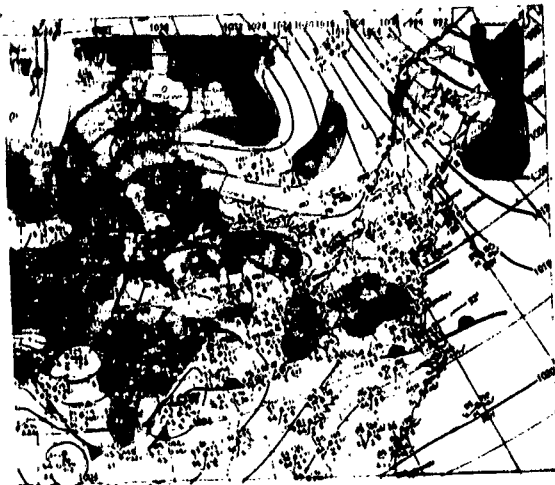


Figure 1. 15 FEBRUARY 1979  
SURFACE MAP AT 1200Z (B/A=33)

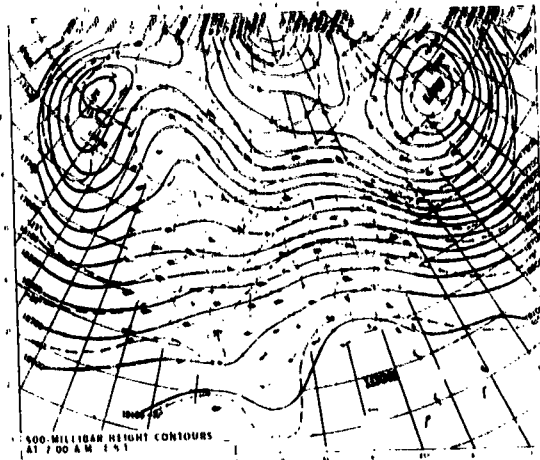


Figure 2. 15 FEBRUARY 1979  
500 MB CHART AT 1200Z (B/A=14)

An example of Type 3 (strong winds) occurred on 1 February and is shown in Figures 3 and 4. Surface B/A = 3, (deep closed low-postfrontal); 500 mb B/A = 4 (deep closed low-post trough)

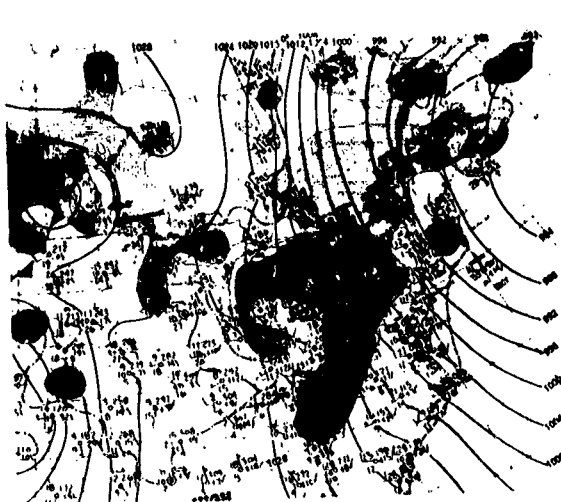


Figure 3. 1 FEBRUARY 1979  
SURFACE MAP AT 1200Z (B/A=3)

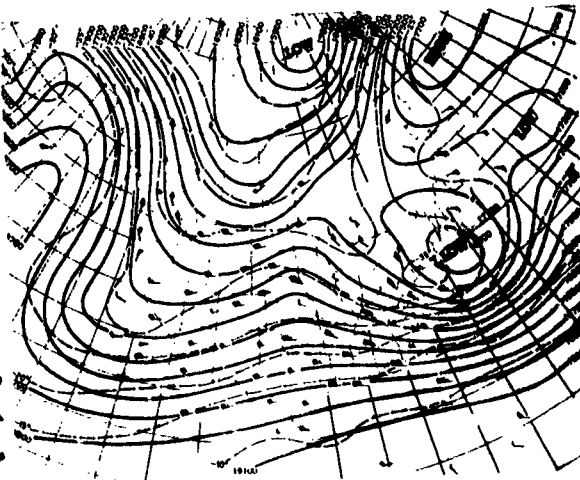


Figure 4. 1 FEBRUARY 1979  
500 MB CHART AT 1200Z (B/A=4)

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850 MB Wind Data

The 850 mb wind data at New York were compared with the PNL data from MTP. In particular the 850 mb speed was analyzed and compared with the maximum hourly wind speed in the succeeding twelve hours. These data are presented in Table 2.

Table 2. MAXIMUM HOURLY WIND SPEED AT MONTAUK POINT  
IN SUCCEEDING 12 HOURS AS A PERCENTAGE OF  
850 MB WIND SPEED AT NEW YORK (486)

MONTH	MONTHLY AVERAGE	DISTRIBUTION BY DIRECTION							
		S	SW	W	NW	N	NE	E	SE
Jan	101	58	87	106	135	101	--	--	--
Feb	87	90	--	68	96	69	--	--	90
Mar	90	43	93	129	104	83	64	--	68
Apr	89	74	104	92	86	70	--	--	--
May	107	107	104	108	120	--	100	133	100
Jun	123	113	170	127	77	110	--	--	--
Jul	102	--	71	130	93	240	--	--	--
Aug	93	--	83	95	92	111	--	108	--
Sep	114	109	130	103	125	109	--	180	140
Oct	108	82	120	100	200	160	--	--	--
Nov	105	--	61	92	128	84	--	350	--
Dec	97	88	63	67	106	155	--	--	--
Avg.	101	85	99	101	114	117	82	193	100

The maximum hourly wind speed at MTP for 1979 was 101 percent of the average 850 mb speed for the year. The values ranged from 123 percent in June to 87 percent in February. The distribution of the comparison by months and direction was also tabulated. However, these values should be viewed only as guides because of the size of this sample. It appears that the largest difference between the observed maximum hourly wind speed and the 850 mb speed occurs with a NW and N wind (E was discounted because of the small sample and the unusually high single value in November).

The conclusion is that the 850 mb wind speed at 1200Z or 0000Z is a good first approximation of the maximum hourly wind in the succeeding twelve hours.

SITE 2: LUDINGTON, MI (LDM)

Data Stratification

The data for LDM were stratified in the same manner as Montauk Point. The data are presented in Table 3.

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Table 3. STRATIFICATION OF WIND SPEEDS AT  
LUDINGTON, MI - 1979 - TYPES 1, 2 AND 3

HOURS					DAYS (1200Z-1200Z)									
Avail		5-7 mps			Avail	Type 1	Type 2	Type 3	None	5-7				
Mon	Data	obs	poss	%	Data	No.	%	No.	%	No.	%	No.	%	Mag
J	744	509	744	68	31	0	0	4	13	25	81	2	6	0
F	633	348	672	55	25	1	4	5	25	18	72	1	4	3
M	672	407	744	61	27	0	0	7	26	19	70	1	4	4
A	529	232	720	44	20	0	0	9	45	9	45	2	10	10
M	744	333	744	45	31	3	10	6	19	19	61	3	10	0
J	720	349	720	49	30	5	17	5	17	20	67	0	0	0
J	744	181	744	24	31	9	29	6	19	9	29	7	23	0
A	744	298	744	40	31	4	13	9	29	17	55	1	3	0
S	720	399	720	55	30	3	10	6	20	20	67	1	3	0
O	744	451	744	61	31	2	7	4	13	25	81	0	0	0
N	0	---	720											
D	0	---	744											

The same general pattern as observed at MTP was also noted at LDM. The maximum percentage (hours) of Type 3 winds occurred in January (68 percent) and the minimum in July (24 percent). The average for the ten month period was 50 percent but would have been higher if data for November and December had been included.

Type 3 winds ranged from a maximum of 25 days (81 percent) in January and October to a minimum of 9 days in July (29 percent).

#### Booz-Allen (B/A) Classification

As in the case of MTP the B/A classification was useful in only a limited way. The moving synoptic systems often cause the B/A types to change rather rapidly as the pressure systems move across the location.

Two synoptic situations are shown. The first example is a Type 1 day (light winds) shown in Figures 5 and 6. The B/A classifications for 10 July are: surface = 35 (flat pressure area); 500 mb = 10 (meridional trough-posttough).

The second example is a Type 3 day (strong, persistent winds) shown in Figures 7 and 8. The B/A classifications for 6 February 1979 are: surface = 14 (open wave cyclone moving SE or E, center S, pretrough); 500 mb = 15 (meridional ridge, portridge).

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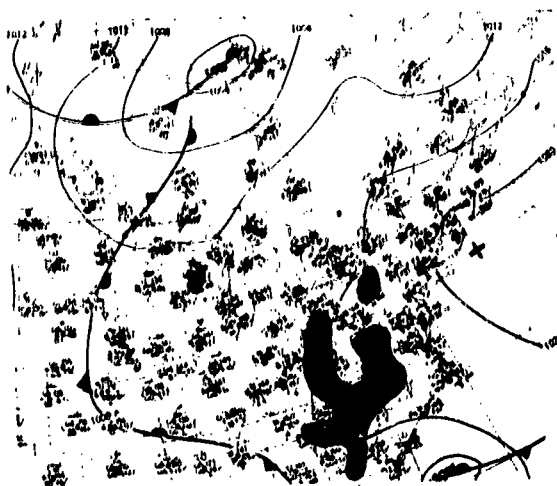


Figure 5. 10 JULY 1979  
SURFACE MAP AT 1200Z (B/A=35)

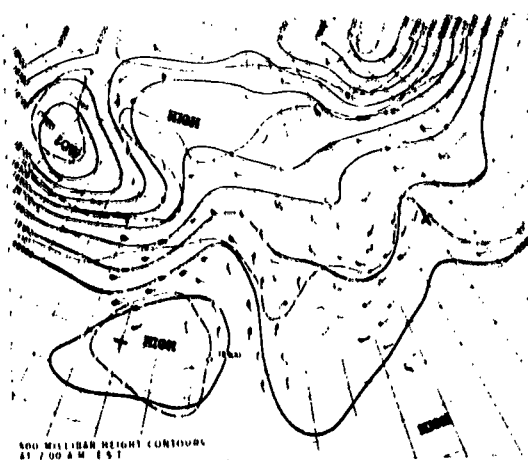


Figure 6. 10 JULY 1979  
500 MB CHART AT 1200Z (B/A=10)



Figure 7. 6 FEBRUARY 1979  
SURFACE MAP AT 1200Z (B/A=14)

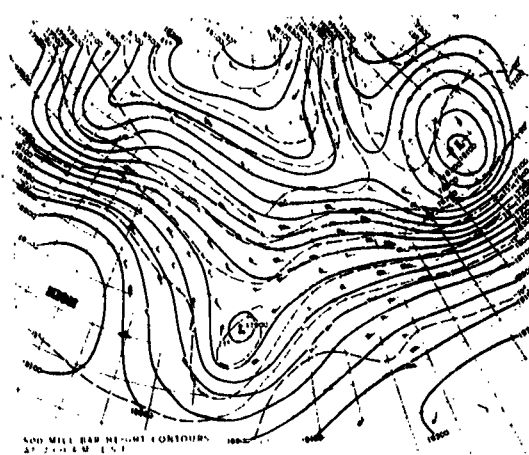


Figure 8. 6 FEBRUARY 1979  
500 MB CHART AT 1200Z (B/A=15)

Stagnant high pressure systems are most favorable for Type 1; strong, moving systems with shifting winds favor Type 3.

#### 850 MB Wind Data

The GRB 850 mb wind speed at 1200Z was logged for each day. The PNL wind data for LDM was classified for each day as Type 1, 2 or 3. The results were tabulated and are presented as percentages of occurrence in Table 4.

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Table 4. 12Z 850 MBS GRB WIND SPEED (KNOTS)  
VS LUDINGTON MI WIND TYPE

WIND SPEED 12Z GRB 850 mbs	PERCENT OCCURRENCE			No. of Cases
	Type 1	Type 2	Type 3	
0- 2 kts	--	--	--	
3- 7	27	35	38	55
8-12	20	33	47	60
13-17	12	10	79	61
18-22	5	18	77	44
23-27	16	16	68	19
28-32	0	8	92	12
33-37	0	0	100	5
38-42	0	0	100	6
43-47	--	--	--	
Total:				262

The data indicate that when the GRB 850 mb wind is equal to or greater than 13 knots, a Type 3 day occurs at LDM 80 percent of the time in the following twenty-four (24) hours (1200Z-1200Z). When 850 mb wind is equal to or greater than 23 knots, Type 3 occurs 83 percent of the time; equal to or greater than 28 knots, 96 percent of the time.

The conclusion is that the 850 mb wind at GRB at 1200Z is a good first approximation of the type of wind day that is likely to occur at LDM.

#### Pressure Gradient Analysis

The pressure gradients on the surface maps in mbs per one hundred fifty (150) nautical miles were measured daily at 1200Z. The pressure difference and the direction of the gradient were logged and compared with the Wind Type (1, 2 or 3). There were 282 cases (instead of 365) in this analysis due to missing data. (The LDM data for November and December 1979 were missing entirely. November and December 1978 data have been obtained and will be included in the final report in order to complete an entire year.)

Table 5 shows the tabulation of the number of occurrences for each pressure difference and the percentage of the total for each type of day. Note that when the pressure gradient is equal to or greater than 3 mbs, a Type 3 day occurs 82 percent of the time; equal to or greater than 4 mbs, 87 percent; equal to or greater than 5 mbs, 92 percent.

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Table 5. LUDINGTON MI. PRESSURE GRADIENT VS SURFACE WIND

## ALL DAYS

		PRESSURE GRADIENT-MBS						
TYPE		0	1	2	3	4	5	6
1	No. of Occurrences	-	15	14	7	6		
	% of Occurrences	-	38	21	13	11	0	0
2	No. of Occurrences	-	14	23	9	5	3	2
	% of Occurrences	-	35	34	16	9	12	5
3	No. of Occurrences	-	11	30	40	44	23	30
	% of Occurrences	-	28	45	71	80	89	95

## GRADIENT 010-090°

		PRESSURE GRADIENT-MBS						
TYPE		0	1	2	3	4	5	6
1	No. of Occurrences	-	1	2	2	2		
	% of Occurrences	-	11	17	15	15		
2	No. of Occurrences	-	6	6	3	3	2	1
	% of Occurrences	-	67	50	23	23	33	13
3	No. of Occurrences	-	2	4	8	8	4	7
	% of Occurrences	-	22	33	62	62	67	88

## GRADIENT 100-180°

		PRESSURE GRADIENT-MBS						
TYPE		0	1	2	3	4	5	6
1	No. of Occurrences	-	3	1	2	2		
	% of Occurrences	-	30	8	11	18		
2	No. of Occurrences	-	3	8	5	1		
	% of Occurrences	-	30	62	26	9		
3	No. of Occurrences	-	4	4	12	8	6	11
	% of Occurrences	-	40	31	63	73	100	100

## GRADIENT 190-270°

		PRESSURE GRADIENT-MBS						
TYPE		0	1	2	3	4	5	6
1	No. of Occurrences	-	10	3	3			
	% of Occurrences	-	56	14	19			
2	No. of Occurrences	-	3	6	2			1
	% of Occurrences	-	17	29	13			25
3	No. of Occurrences	-	5	12	11	13	8	4
	% of Occurrences	-	28	57	69	100	100	75

## GRADIENT 280-360°

		PRESSURE GRADIENT-MBS						
TYPE		0	1	2	3	4	5	6
1	No. of Occurrences	-	2	3	0	2		
	% of Occurrences	-	67	17		11		
2	No. of Occurrences	-	1	5	3	1	1	
	% of Occurrences	-	33	28	30	6	14	
3	No. of Occurrences	-		10	7	15	6	13
	% of Occurrences	-		56	70	83	86	100



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These data were further subdivided into quadrants to examine local effects caused by Lake Michigan. The results are tabulated in Table 5. Note that the percentage of Type 3 days decreases (66 vs 82) for the 010-090 quadrant (due to frictional effect) while the 190-270 (86 vs 82) and 280-360 (85 vs 82) quadrants have an increase (due to less friction over Lake Michigan).

The conclusion is that when a pressure gradient of equal to or greater than 3 mb exists at 1200Z across LDM a Type 3 day is expected to occur at least 66 percent of the time and more likely to occur 82-86 percent of the time.

SITE 3: AMARILLO, TX (AMA)

The PNL data for AMA were stratified and classified in a manner similar to MTP and LDM. In addition the 850 mb wind speed at 1200Z was tabulated and compared with the number of consecutive hours (up to 24 hours) of PNL wind speeds equal to or greater than 7 mps. Figure 9 shows this data.

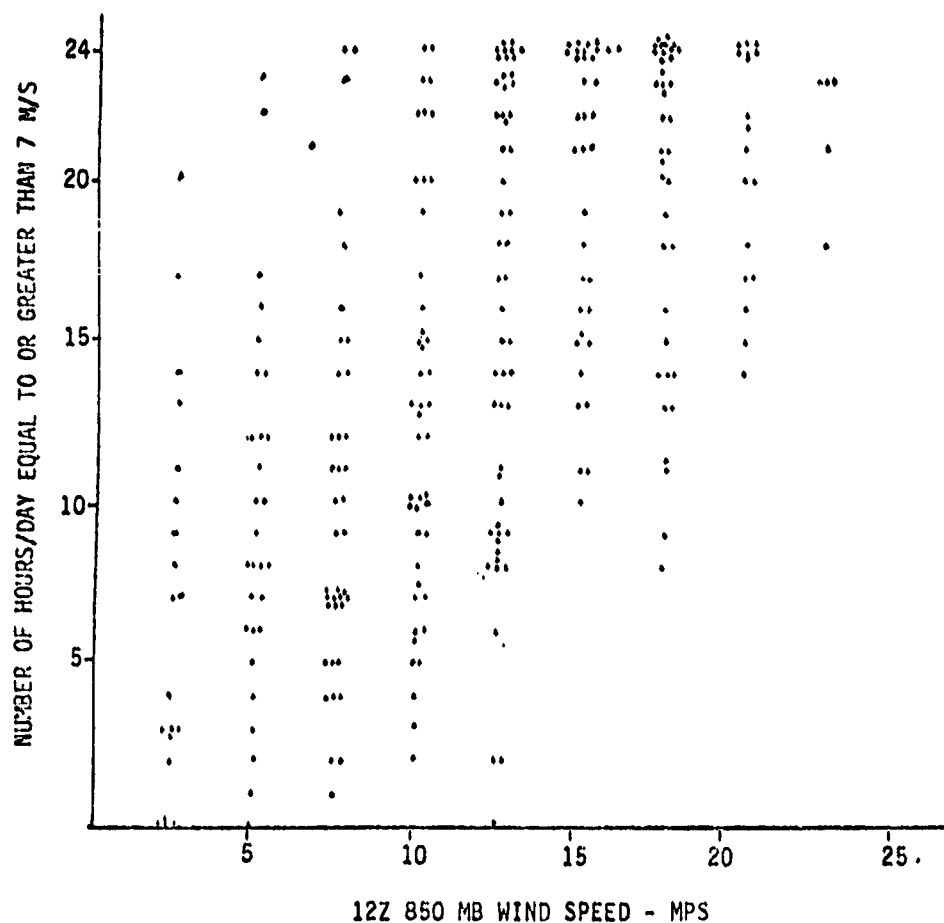


Figure 9. 850 MB WIND SPEED AT 1200Z VS THE NUMBER OF.  
CONSECUTIVE HOURS OF WINDS EQUAL TO OR GREATER THAN 7 MPS  
AMARILLO, TX (1979)

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Although there is a wide scatter of the tabulation there is a definite trend indicated. The conclusion is that the stronger the wind at 850 mbs at 1200 the greater number of consecutive hours of wind speeds equal to or greater than 7 mps.

An example of a Type 1 situation (light winds) is shown in Figures 10 and 11 for 12 February 1979. The surface B/A = 35 (flat pressure area); the 500 mb B/A = 14 (meridional ridge, prridge). An example of a Type 3 situation (strong persistent winds) is shown in Figures 12 and 13 for 20 February 1979. The surface B/A = 24 (meridional trough, pretrough); the 500 mb B/A = 9 (meridional trough, pretrough). The 20 February situation was one of a series of systems moving across the AMA area. Type 3 winds persisted for ninety-six (96) consecutive hours from 19 February through 22 February.

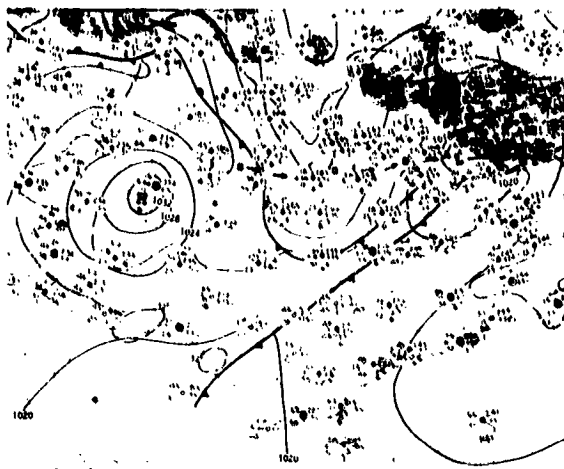


Figure 10. 12 FEBRUARY 1979  
SURFACE MAP AT 1200Z (B/A=35)

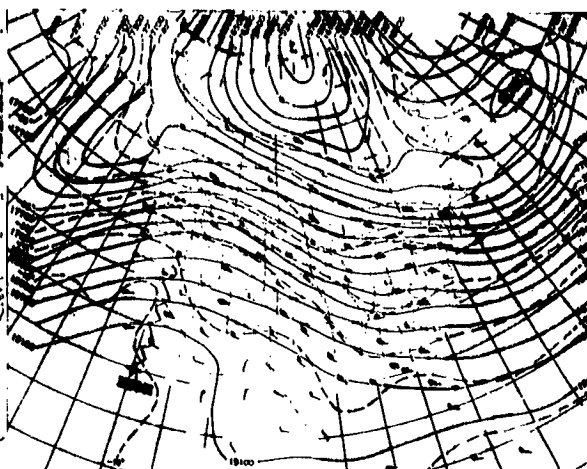


Figure 11. 12 FEBRUARY 1979  
500 MB CHART AT 1200Z (B/A=14)

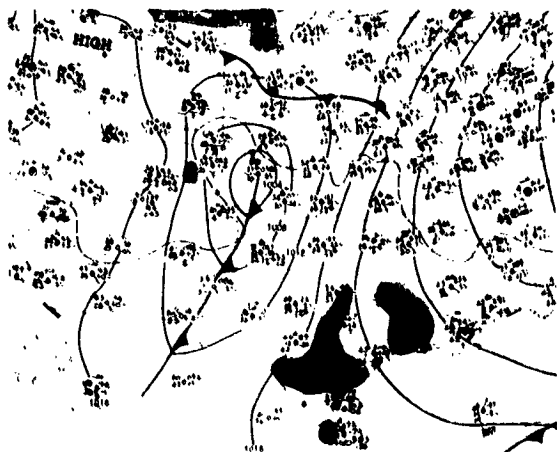


Figure 12. 20 FEBRUARY 1979  
SURFACE MAP AT 1200Z (B/A=24)

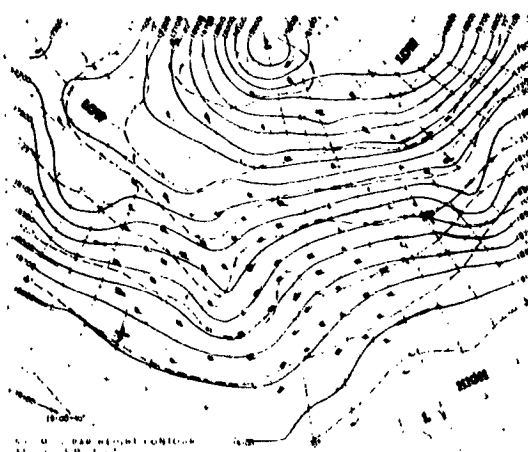


Figure 13. 20 FEBRUARY 1979  
500 MB CHART AT 1200Z (B/A=9)

The conclusion is that a long wave trough over the Rocky Mountains with a series of short wave troughs at 500 mbs along with associated surface weather systems is a favorable pattern for Type 3 days. A weak ridge over the Rocky Mountains is less favorable.

#### SITE 4: SAN GORGONIO, CA (SAG)

This site is discussed in detail in Part 2 of this report. The B/A types had high degree correlation with both Type 1 and Type 3 days.

#### CONCLUSIONS

##### Montauk Point, NY (MTP)

In 1979 there was a total of 3,436 hours of wind speeds equal to or greater than 7 mps. This represents 41 percent of the hours observed.

Type 3 days occurred 52 percent of the days in 1979 ranging from a high value of 82 percent in January to a low value of 21 percent in July.

The 850 mb wind speed is a good first approximation of the maximum hourly wind in the next 12 hours.

##### Ludington, MI (LDM)

When the GRB 850 mb wind is equal to or greater than 13 knots a Type 3 day occurs at LDM 80 percent of the time in the following 24 hours.

When a pressure gradient equal to or greater than 3 mbs (across 150 nautical miles) exists at 1200Z across LDM a Type 3 day is expected to occur at least 66 percent of the time and more likely to occur 82-86 percent of the time.

##### Amarillo, TX (AMA)

The stronger the wind at 850 mb the greater the number of consecutive hours of wind speeds equal to or greater than 7 mps.

A long wave trough over the Rocky Mountains with a series of short wave troughs at 500 mbs with associated surface weather systems is a favorable pattern for Type 3 days. A weak ridge over the Rocky Mountains is less favorable.

##### San Gorgonio, CA (SAG)

The B/A types had a high degree of correlation with Type 1 and Type 3 days.

#### ACKNOWLEDGMENTS

This research was supported by Battelle Pacific Northwest Laboratories (PNL) under Contract Number B-B6618-AN awarded to Murray and Trettel (M/T) in February 1981.

This study represents the collective efforts of a number of individuals in three organizations. We acknowledge, with appreciation, the cooperation and assistance of A. H. Miller and H. L. Wopley (PNL) and C. Notis, Freese-Notis. Many members of the M/T staff contributed in one way or another to this study. In particular we wish to acknowledge D. R. Davidson, M. D. Fitzgerald and S. F. Larson for their assistance in working with the above personnel in the data logging from the wind data furnished by PNL and the weather data logging from the synoptic charts furnished by the National Climatic Center (NCC); J. A. Greer for the operation of our word processor in the typing of the report; J. R. Murray and J. P. Bradley for their assistance in preparing the original proposal and their assistance, suggestions and guidance throughout the entire project.

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## APPENDIX

## The Booz-Allen Surface Types

Type No.	Description
1.	<u>Deep Closed Low (deepening or mature cyclone)</u>
a.	Center North
1	(1) Advance Zone
2	(2) Prefrontal and frontal (occlusion or warm front) (or trough)
3	(3) Postfrontal (or trough) (cold front or occlusion)
4	(4) Warm sector
5	(5) Prefrontal and frontal (cold)
b.	Center South
6	(1) Advance Zone
7	(2) Pretrough
8	(3) Posttrough
2.	<u>Open Wave Cyclone Moving SE or E</u>
a.	Center North
9	(1) Advance Zone
10	(2) Prefrontal (warm)
11	(3) Warm sector
12	(4) Prefrontal and frontal (cold)
13	(5) Postfrontal (cold)
b.	Center South
14	(1) Pretrough
15	(2) Posttrough
3.	<u>Open Wave Cyclone Moving NE</u>
a.	Center North
16	(1) Frontal (warm)
17	(2) Warm sector
18	(3) Prefrontal and frontal (cold)
19	(4) Postfrontal (cold)
b.	Center South
20	(1) Advance Zone
21	(2) Pretrough, warm front zone
22	(3) Posttrough
23	(4) Warm sector
4.	<u>Meridional Trough (N-S or tilted)</u>
24	a. Pretrough
25	b. Posttrough
26	c. Trough or frontal zone
5.	<u>Inverted Trough</u>
27	a. Pretrough
28	b. Posttrough
6.	<u>Ridge, or High, Center South (or same latitude)</u>
29	a. Preridge
30	b. Poutridge

The Booz-Allen Surface Types (Continued)	
Type No.	Description
	7. <u>High, Center North (or same latitude)</u>
31	a. Preinverted ridge
32	b. Center
33	c. Postinverted ridge
34	d. E-W gradient
	8. <u>Flat Pressure Area</u>
35	Cols or other areas (except high centers) where wind is indeterminate.

The Booz-Allen 500-millibars Types	
Type No.	Description
	1. <u>Deep Closed Low</u>
	a. Center North
1	(1) Pretrough
2	(2) Posttrough
	b. Center South
3	(1) Pretrough
4	(2) Posttrough
	2. <u>Weak Closed Low</u>
	a. Center North
5	(1) Pretrough
6	(2) Posttrough
	b. Center South
7	(1) Pretrough
8	(2) Posttrough
	3. <u>Meridional Trough (N-S or tilted)(including transitional)</u>
9	a. Pretrough
10	b. Posttrough
	4. <u>Basically Zonal</u>
11	a. Westerly flow
12	b. Preminor trough
13	c. Postminor trough
	5. <u>Meridional Ridge</u>
14	a. Preridge
15	b. Postridge
	6. <u>High, Center North (or same latitude)</u>
16	a. Preinverted ridge
17	b. Center
18	c. Postinverted ridge
19	d. E-W gradient
	7. <u>Flat Pressure Area</u>
20	Cols or other transitional areas (except highs) where wind is indeterminate and there is no convergence.

THE USEFUL POTENTIAL OF USING EXISTING DATA TO  
UNIQUELY IDENTIFY PREDICTABLE WIND EVENTS AND REGIMES  
PART II

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ABSTRACT

Wind data from four DOE sites for the year 1979 was stratified and found to naturally fit into a few unique groups. These were compared with synoptic weather patterns using the Booz-Allen classification system. Strong relationships became evident between a particular synoptic type and wind events for each site. Statistics indicate certain patterns which result in strong winds, ( $> 7$  m/s, 15.6 mph), and some that result in weak winds. For each site there is a preferred wind direction associated with the strongest speed. Important relationships have also been found comparing 850-mb and surface wind. Additionally, comparisons between pressure gradient and wind speed for a given gradient direction show some significant relationships. It can be stated that the overall results of the study show that by using existing data for any site, the winds can be characterized and correlated with synoptic weather patterns. As a result, reliable wind forecasts can be made for utility companies for the purpose of power generation.

INTRODUCTION

During the period May through October of 1979 a few private weather consulting companies (including the author's company) were under contract with Battelle Pacific Northwest Laboratories to forecast winds up to 24 hours in the future for the various DOE wind turbine generating sites scattered throughout the United States. In some of these locations there was no National Weather Service reporting station, thus eliminating any real time data. In addition, forecast verification of any kind was unavailable until about July or August. When some forecast verification was available there was a three month lag. In other words, verifications received in July were actually the May verifications. With these severe handicaps, it was almost as if forecasting blindfolded. Therefore, the forecasts were naturally less than desirable. However, there was some skill shown, especially by several of the weather consulting companies.

It became apparent following that forecasting project that each of the sites had its own very unique wind characteristics. For example, a northwest (NW) gradient will result in a strong southwest (SW) wind at one site and a strong (NW) wind at another site. In order for forecasts to become reliable enough to be used by utility companies, it was felt that research was necessary to study the intricate relationships between synoptic and mesoscale weather patterns, topographic influences, and a particular wind event at each site. In turn, this would lead to finding forecasting rules and site characterization. Therefore, the decision was made by Battelle personnel to undertake such a study. Contracts were then awarded to two private weather consulting companies, Murray and Trettel, Inc. of Northfield, Illinois and the author's company.

Research on this project started in early February, 1981 and is expected to be completed by December, 1981 with the writing of a final report. It is the purpose of this paper to report on the progress and findings of this study up to the present time. The four sites which have been designated for study by Freese-Notis Weather include San Geronio, California; Clayton, New Mexico; Boone, North Carolina; and Montauk, New York.

#### DATA SOURCES AND PROCEDURE

There have been three basic sources of data used to conduct this research. These include Battelle - furnished time-series plots for each of the four sites for the year 1979, digitized hourly averaged observed wind speed and direction data, and National Climatic Center (NCC) - furnished synoptic weather maps on microfilm.

The time-series plots were carefully analyzed according to certain criteria for speed and direction and a stratification was performed. It was found the plots naturally fit into five or six distinct groupings per site. That alone suggests certain relationships between synoptic patterns, topographic effects and wind events at each site. An example of a time-series plot for San Geronio for May, 1979 is shown in Figure 1. Table 1 lists the wind speed and direction stratifications

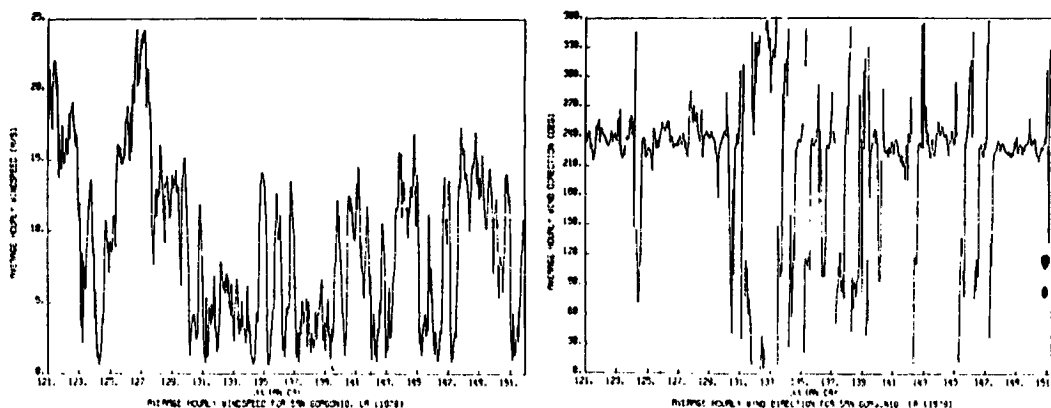


FIGURE 1. TIME-SERIES PLOTS FOR SAN GORONIA FOR MAY, 1979  
SHOWING THE AVERAGED HOURLY WIND SPEED AND WIND DIRECTION



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for San Geronio. The other three sites were stratified in a similar fashion.

TABLE 1. WIND SPEED AND DIRECTION STRATIFICATION  
FOR SAN GERONIO

**Wind Speed**

- Type 1 - Diurnal character with 7 or 8 day duration. Speed ranges from roughly 0.5 m/s to 12 m/s.
- Type 2 - Generally light wind situation lasting from a couple days to as many as 10. Speed ranges from about 0.5 m/s to 0.5 m/s.
- Type 3 - Quite variable in speed with peaks of 15-20 m/s and minimums somewhere between 0.5 m/s. Duration can be from 2 to about 5 days.
- Type 4 - Duration of about 1 day and speed up to 15 m/s. Quite isolated and more likely to occur in cold season.
- Type 5 - Strongest type. Speeds exceed 10 m/s for a while and last from one to three days. Speed minimums are usually greater than 15 m/s.
- Type 6 - Very narrow, isolated spikes lasting a few hours at most and reaching speeds of up to 15 m/s quite rare.

**Wind Direction**

- Type 1 - Great diurnal variation from 0° to 160° with no apparent direction preference. Lightest speed regime (less than 6 m/s). Can last 1 week or more.
- Type 2 - Strongest speed type with 110° to 160° direction. Can last a few days reaching speeds up to 15 m/s. Frequent type.
- Type 3 - Diurnal type from SE veering to NW with definite preference at about 150° for a few hours. Can last for a few days. Speeds can reach 15 m/s and is usually associated with speed type 1.
- Type 4 - Same as from NW backing to SE with definite preference at about 150°. Can last for a week or more. Speeds generally less than 15 m/s for peaks. May be similar to type 1.
- Type 5 - Direction is NW for 5-10 hours then suddenly SE to NE for a brief time. Speeds less than 1 m/s for peaks. This type occurs infrequently but when it does persist for a few days. Usually occurs with a 1 speed type.

The digitized data was used to record the actual speed and direction at the sites for 1200 and 0000 GMT for the entire year 1979. Those times were picked to coincide with the NCC data.

The NCC microfilm data used, included surface maps, 500-mb, 700-mb, and 850-mb surfaces for the United States. These maps were carefully examined and a particular synoptic pattern was noted during 0000 and 1200 GMT for the sites. In order to facilitate and simplify the description of the patterns, some kind of classification system was necessary. It was decided that a classification system devised by Booz-Allen (Hollanger, 1968) would be used for this purpose. The Booz-Allen (B-A) system consists of 35 surface types and 20- 500-mb types. It was decided to also apply the 500-mb B-A types to the 700-mb surface. For the 850-mb surface, the wind speed and direction (estimated at that level) was recorded for later comparisons with site winds. Table 2 lists the B-A surface types. The B-A 500-mb types are not shown here because research on the upper air patterns is not complete. This classification system proved to be very beneficial to the project. At times it was rather difficult to decide what B-A designation a particular synoptic pattern should have, i.e. "pretrough" or "postridge", etc. But the resulting winds in these cases are quite similar. In fact, some thought may be given to combine these B-A types into one, later in the project.

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TABLE 2. BOOZ-NIEN SURFACE TYPES

Type No.	1.	DEEP CLOSED LOW (DEEPENING OR MATURE CYCLONE)
	a.	CENTER NORTH
	1.	(1) ADVANCE ZONE
	2.	(2) PREFRONTAL AND FRONTAL (OCCLUSION OR WARM FRONT) (OR TROUGH)
	3.	(3) POSTFRONTAL (OR TROUGH)
	4.	(4) WARM SECTOR
	5.	(5) PREFRONTAL AND FRONTAL (COLD)
	b.	CENTER SOUTH
	6.	(1) ADVANCE ZONE
	7.	(2) PREFRONTAL
	8.	(3) POSTTROUGH
	2.	OPEN WAVE CYCLONE MOVING SE OR E
	a.	CENTER NORTH
	9.	(1) ADVANCE ZONE
	10.	(2) PREFRONTAL (WARM)
	11.	(3) WARM SECTOR
	12.	(4) PREFRONTAL AND FRONTAL (COLD)
	13.	(5) POSTFRONTAL (COLD)
	b.	CENTER SOUTH
	14.	(1) PREFRONTAL
	15.	(2) POSTTROUGH
	3.	OPEN WAVE CYCLONE MOVING NE
	a.	CENTER NORTH
	16.	(1) FRONTAL (WARM)
	17.	(2) WARM SECTOR
	18.	(3) PREFRONTAL AND FRONTAL (COLD)
	19.	(4) POSTFRONTAL (COLD)
	b.	CENTER SOUTH
	20.	(1) ADVANCE ZONE
	21.	(2) PREFRONTAL, WARM FRONT ZONE
	22.	(3) POSTTROUGH
	23.	(4) WARM SECTOR
	4.	MERIDIONAL TROUGH (N-S OR TILTED)
	a.	PREFRONTAL
	b.	POSTTROUGH
	c.	TROUGH OR FRONTAL ZONE
	5.	INVERTED TROUGH
	a.	PREFRONTAL
	b.	POSTTROUGH
	6.	RIDGE, OR HIGH, CENTER SOUTH
	a.	PRERIDGE
	b.	POSTRIDGE
	7.	HIGH, CENTER NORTH (OR SAME LATITUDE)
	a.	PRERIDGE
	b.	CENTER OVER SITE
	c.	POSTRIDGE
	d.	E-W GRADIENT (ISOBARS ORIENTED E-W)
	8.	FLAT PRESSURE AREA
	15.	COLS OR OTHER AREAS (EXCEPT HIGH CENTERS) WHERE WIND IS INDETERMINATE

Each of the B-A types for the various pressure surfaces was compared with the observed wind speed and direction and with the stratified wind groups. Naturally, in some cases certain B-A types occurred so infrequently that it was decided to ignore them. The means and standard deviations were calculated for each relationship to get an idea of how each sample was distributed.

Due to the importance of the cut-in speed of 6.2m/s (14mph) for the MOD-2 Wind Turbine Generator, considerable work has also been done on the  $\geq 7$ m/s (15.6mph) threshold. For each B-A type, the number of occurrences of  $\geq 7$ m/s wind speed was calculated in percent. To further study speed relationships, the perpendicular pressure gradient across 335 kilometers (180 nautical miles) centered at the site was determined for 0000 GMT and 1200 GMT for each site. The gradient direction was also recorded so that the relationship between gradient direction, gradient strength, and wind speed could be studied. Finally, the ratio between the surface wind speed and 850-mb speed was calculated and compared with B-A types.

## DISCUSSION AND RESULTS

### San Gorgonio

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Prior to the start of this research it was the consensus that this site would be the most difficult in terms of forecasting. However, after a brief glance at the data, it became quite obvious that San Geronio displays the most consistent relationships between synoptic weather patterns and wind events. In order to better understand the wind characteristics at this site, a brief topographic description is helpful. The site is located in a basically east-west mountain pass in southeastern California. The elevation is approximately 341m (1120 ft.) and 5000-8000 foot mountains lie to the north and south. Needless to say this topography plays a very important role in determining the wind events at the site.

It does not take much investigation to see that by far the favorite wind direction at the site is southwest (SW) to west southwest (WSW), whenever speeds exceed 6m/s. The typical time series plot shown in Figure 1 clearly demonstrates this characteristic. Furthermore, a study of Table 3 also shows this relationship. In this Table the mean direction and its standard deviation ( $\sigma$ ), the mean speed and  $\sigma$ , and the %  $\geq 7$ m/s are recorded for the appropriate B-A type. The B-A types which have two mean directions recorded is due to the bi-modal character of these types. The bi-modal character is caused by diurnal effects when the pressure gradient is very weak or when the gradient direction is northeast (NE) through south (S). Under these conditions the wind tends to be strong

TABLE 3. WIND STATISTICS FOR SAN GERONIO												
SAN GERONIO												
Surface						850 mb						
Class No.	No. of Obs.	Average Direction	Sigma	Average Speed	Sigma	Surface	Average Direction	Sigma	Average Speed	Sigma	Surface to 850 Ratio	
1	1	---	---	5.2	5.2	40	---	---	5.8	5.9	---	---
2	1	---	---	---	---	---	---	---	---	---	---	---
3	17	253	64	8.8	6.7	60	275	52	10.6	1.7	1.081	---
4	1	---	---	---	---	---	---	---	---	---	---	---
5	26	205	80	9.2	6.6	60	252	54	9.1	1.3	1.011	---
6	2	---	---	---	---	---	---	---	---	---	---	---
7	5	---	---	---	---	---	---	---	---	---	---	---
8	6	---	---	3.2	2.5	11	---	---	9.1	2.3	---	---
9	0	---	---	---	---	---	---	---	---	---	---	---
10	0	---	---	---	---	---	---	---	---	---	---	---
11	0	---	---	---	---	---	---	---	---	---	---	---
12	11	228	45	8.0	1.1	67	271	47	6.7	1.0	1.191	---
13	11	215	41	11.6	5.0	82	105	40	11.8	1.0	1.981	---
14	2	---	---	---	---	---	---	---	---	---	---	---
15	0	---	---	---	---	---	---	---	---	---	---	---
16	0	---	---	---	---	---	---	---	---	---	---	---
17	0	---	---	---	---	---	---	---	---	---	---	---
18	4	---	---	---	---	---	---	---	---	---	---	---
19	5	---	---	---	---	---	---	---	---	---	---	---
20	0	---	---	---	---	---	---	---	---	---	---	---
21	0	---	---	---	---	---	---	---	---	---	---	---
22	0	---	---	---	---	---	---	---	---	---	---	---
23	0	---	---	---	---	---	---	---	---	---	---	---
24	2	210	71	7.5	5.6	58	266	58	8.0	1.6	---	---
25	22	215	42	10.6	5.0	76	227	41	8.1	4.9	1.918	---
26	14	220	69	9.5	4.7	8	261	89	8.3	4.6	1.109	---
27	29	207/228	18/45	1.3	2.9	16	66	69	8.1	1.1	1.617	---
28	211	107/228	40/60	8.1	4.9	67	106	72	8.4	1.0	1.590	---
29	20	214	45	10.2	5.6	74	106	57	6.8	1.6	1.500	---
30	4	---	---	---	---	---	---	---	---	---	---	---
31	89	210	18	10.5	5.1	78	115	47	8.0	1.7	1.551	---
32	10	---	---	---	---	---	---	---	---	---	---	---
33	11	110/288	12/44	7.8	3.3	12	---	---	7.8	3.3	1.00	---
34	121	90/294	43/45	1.9	1.0	71	58	72	7.1	1.1	1.765	---
35	44	107/288	26/14	1.1	7.8	50	248	74	4.3	1.0	1.76	---

SW during the day and light easterly (E) later at night and early morning. Figure 2 graphically shows this bi-modal phenomenon for B-A type 28. However, note the predominance of the SW direction. More than 80% of the time the wind is SW for this B-A type. Generally, the strong wind types, all with direction from 220°- 260°, are associated with a posttrough, a preridge, or a post cold frontal situation. This implies a very

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important phenomenon regarding pressure for this site. As long as the pressure is lower to the east of the site, the wind will blow quite strong (generally at least 7m/s and quite often  $>15\text{m/s}$ ) between  $220^\circ$  -  $260^\circ$ . The exact strength is generally dependent upon the pressure gradient. On the other hand, the odds for a very light wind ( $\leq 6\text{m/s}$ ) are very high with low pressure to the west of the site. A mesoscale

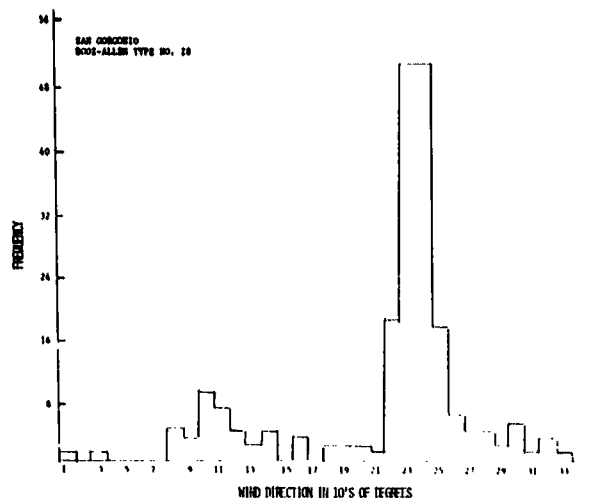


FIGURE 2. TYPICAL WIND DIRECTION FOR SAN GORGONIO  
FOR BOOZ-ALLEN SURFACE TYPE 28.

feature that sometimes occurs is a weak trough of low pressure just west of the site followed by the usually strong Pacific High. If not analyzed carefully, this weak trough might be missed. This will result in an over estimate of the wind speed. The above pressure rules are so universal at San Gorgonio that one has to double check for possible error if something contradictory to the rules is observed.

Referring to Table 3 once again, note that with a few B-A types a mean speed and  $\sigma$  is given without any direction. This is due either to the very small number of observations, or the great scattering of the data in some cases making the mean direction meaningless. This occurs with very light gradients. The most frequent B-A types are generally numbers 27-29, 31, and 34. The Table also shows the 850-mb mean direction and  $\sigma$ , the mean speed and  $\sigma$ , and the ratio of the surface speed to the estimated 850-mb speed for the appropriate B-A surface type. It is interesting to note quite a few occurrences of stronger surface winds than 850-mb winds especially for the posttrough or postfront types. Finally, the Table also shows the  $\% \geq 7\text{m/s}$  for the particular B-A surface type. Not surprisingly, large percentage values appear for the typical and frequent B-A types for the site and small values are common for the pretrough types. The author suspects this correlation would be even stronger, but in some cases it was rather difficult for the researcher to decide which B-A type should be assigned for a particular synoptic situation. A great deal of individual judgement went into the decision. We are currently in the process of combining some of the B-A surface types. For example, we are combining B-A types 3, 13, 19, 25, 28, 29, and 31 due to the similarity in isobaric orientation for these types. In a similar manner numbers 2, 4, 12, 18, 24, 27, 30 and 33 are being combined.

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We are designating the first group as postfrontal or posttrough and the second group as prefrontal or pretrough. Preliminary indications with this approach give encouraging results. Another glance at the Table still suggests some inconsistencies however. There appear to be a significant number of cases with the designation of "pretrough" or "prefrontal" that have winds  $>7\text{m/s}$ . The secret here is the orientation of the isobars from west to east as a low pressure center or meridional trough passes off to the north of the site. Under this situation, a fairly strong southwest wind can result. On the other hand if a high is located to the north (east to west pressure gradient of B-A number 34) the result is very weak wind of  $<5\text{m/s}$  ( $<11.2\text{mph}$ ) even with a fairly tight pressure gradient. Typical surface analyses of a strong and weak wind situations are shown in Figure 3.

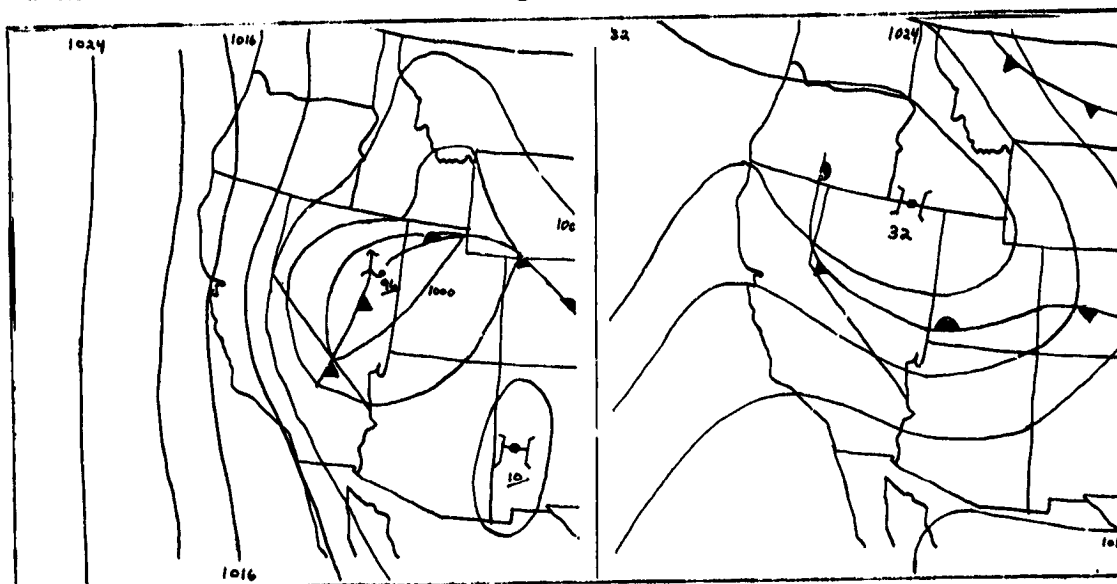


FIGURE 3. TYPICAL SURFACE MAP DESCRIPTION ASSOCIATED WITH STRONG WIND (LEFT) AND WEAK WIND (RIGHT) FOR SAN GORGONIO.

Finally, Figure 4 shows the relationship between pressure gradient and wind speed for a given gradient direction for all sites. As far as San Gorgonio is concerned, the curves beautifully demonstrate the very light wind conditions for the gradient directions NE through SW. For the westerly (W) gradient, we do notice a speed average of  $\approx 8\text{m/s}$  for 1,2,4,5, and 6-mb gradients. The dip at 3-mb is probably due to an insufficient data sample. This Figure helps to explain the above mentioned inconsistencies. For, if low pressure is to the N or NW of the site, the gradient direction is more than likely to be W. For the NW and N gradients which truly imply lower pressure to east and high pressure west, the speed increases dramatically as the pressure gradient increases. As of the writing of this paper, similar graphs showing the relationship between pressure gradient and wind direction for a given gradient direction are not completed. Also, the 500-mb and the 700-mb data has not been fully analyzed yet but it is suspected that this data will not be as useful as that of the surface and 850-mb.

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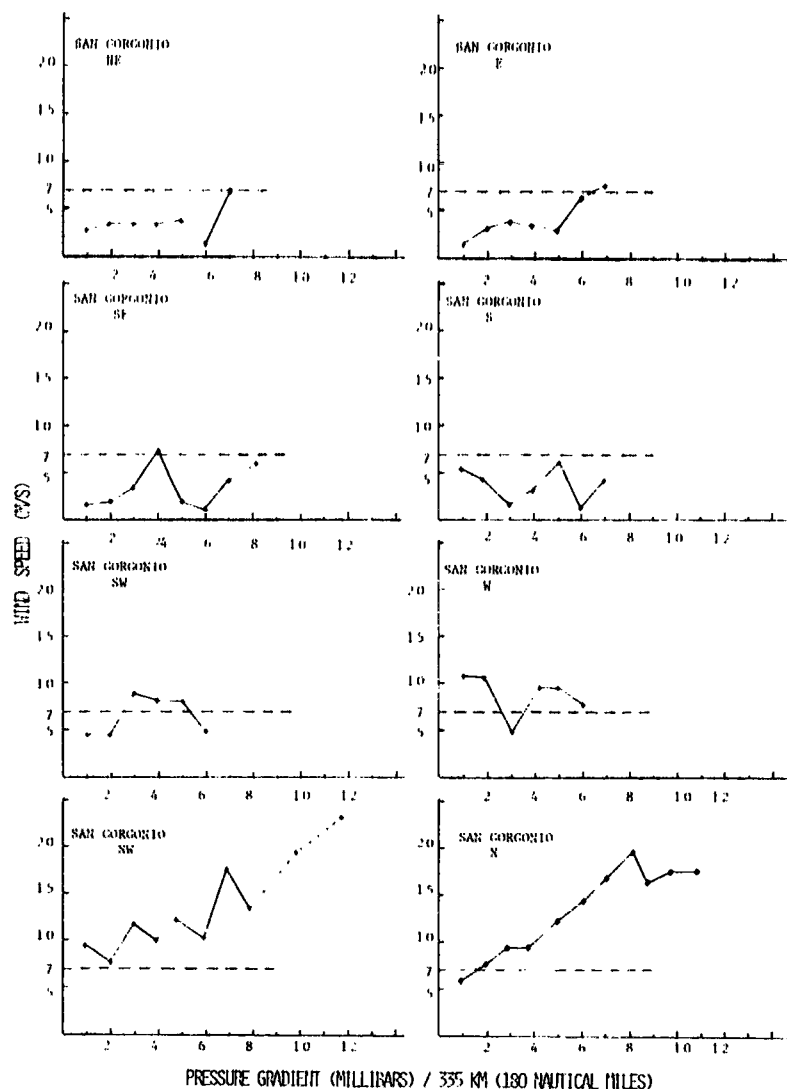


FIGURE 4. CURVES RELATING PRESSURE GRADIENT AND WIND SPEED FOR SAN GORGONIO FOR 8 GRADIENT DIRECTIONS. THE HORIZONTAL DASHED LINE IS THE 7 M/S THRESHOLD. OTHER FINE DASHED LINES IMPLY NO DATA AVAILABLE BETWEEN POINTS.

### Clayton

Clayton is located in the extreme northeast corner of New Mexico and has an elevation of 1534m (5030 ft). The foot hills of the Rocky Mountains begin 10 miles west of the site. This site is considerably more complex in terms of weather regimes and site wind events than the San Gorgonio site. However, after a careful examination of the data the "secrets" of the site are being revealed.

As can be seen from Table 4, the most common B-A types are 24-26, 31, 33, and 34. All types have mean direction between  $160^{\circ}$  and  $230^{\circ}$  except for types 3, 13, 25, and 31 which show a W to NW direction. However, the standard deviations are quite large suggesting the great

variability and erratic character of this site. In fact, there is a

CLAYTON											
Surface					850 mb						
Class	No.	Average Direction	Average Speed	% / Hrs Surface	Average Direction	Average Speed	Average Sigma	Surface To 850 Ratio			
1	16	212	5.8	9.4	2.0	88	236	12	13.1	3.0	.718
2	3	224	5.2	9.5	2.9	76	107	43	13.1	9.5	.715
3	6	225	4.6	10.6	2.3	100	222	48	12.8	7.8	.828
4	11	202	4.5	9.7	4.8	95	245	51	12.1	5.0	.760
5	0										
6	3										
7	16		11.4	5.6	94			12.2	3.6		.945
8	1										
9	20	199	5.6	8.5	2.5	85	260	47	10.0	9.4	.850
10	16	194	4.4	8.2	3.0	64	205	65	10.6	4.6	.735
11	10	129	6.3	9.5	4.1	68	156	57	10.9	5.2	.862
12	7			6.9	4.3	67			7.0	2.4	.986
13	0										
14	0										
15	11	210	1.9	9.0	4.2	73	236	29	11.0	5.3	.818
16	9			8.1	3.3	62			9.2	4.1	.880
17	0										
18	0										
19	0										
20	0										
21	0										
22	0										
23	0										
24	67	198	4.3	7.0	2.5	57	235	47	10.2	4.0	.886
25	12	297	8.1	6.6	2.6	48	293	65	9.8	4.5	.873
26	52	202	7.0	7.1	2.6	59	243	53	9.6	4.6	.833
27	18	162	6.9	7.1	2.9	44	163	51	9.2	3.4	.772
28	8				2.7	50			9.2	3.8	.783
29	1										
30	14	188	4.5	6.5	2.0	43	238	43	6.6	4.3	.985
31	99	291	7.5	6.7	3.0	49			8.5	4.5	.788
32	5										
33	77	160	7.3	6.6	2.5	52	186	68	7.0	3.3	.943
34	64	156	6.7	6.5	3.0	44			7.9	4.4	.823
35	26	186	6.7	5.2	2.3	29	256	54	6.1	2.5	.852

great diurnal effect going on at any time of the year. The preferred direction at Clayton is somewhere between  $180^{\circ}$ - $360^{\circ}$  for the strongest speeds with the prevailing wind being SW. Except for quite strong pressure gradients, the wind will generally blow quite strong from the SW during the day at  $> 7\text{m/s}$  and light and variable at night and early morning. A good correlation exists between the surface direction and 850-mb direction for the great majority of the B-A types. Generally, the two don't vary by more than  $20^{\circ}$ - $40^{\circ}$ . The ratio between the surface and 850-mb speeds is generally between 0.7 and 0.9 for all the synoptic types. Speeds can be strong at the site from all directions except for NE through ESE. In these cases the speeds are generally  $< 4\text{m/s}$ .

Clayton is notorious for blowing against the gradient. For example, an E gradient can result in a NW wind. In some cases, especially in the summer half of the year, weak low pressure is located in western Kansas. With this situation, Clayton will blow from the SW right across the isobars into the low. If one had to choose the most common synoptic pattern for Clayton it would have to be the lee-side trough either just west, over, or just east of the site. Figure 5 shows a strong and a weak synoptic type for Clayton.

Figure 6 for Clayton graphically shows a fairly strong wind for most gradient directions. The outstanding exception is the SE gradient which shows light winds for all pressure gradient strengths. E and S gradients are also fairly weak.

During the progress of this research the following "rules of thumb" have been observed for Clayton:

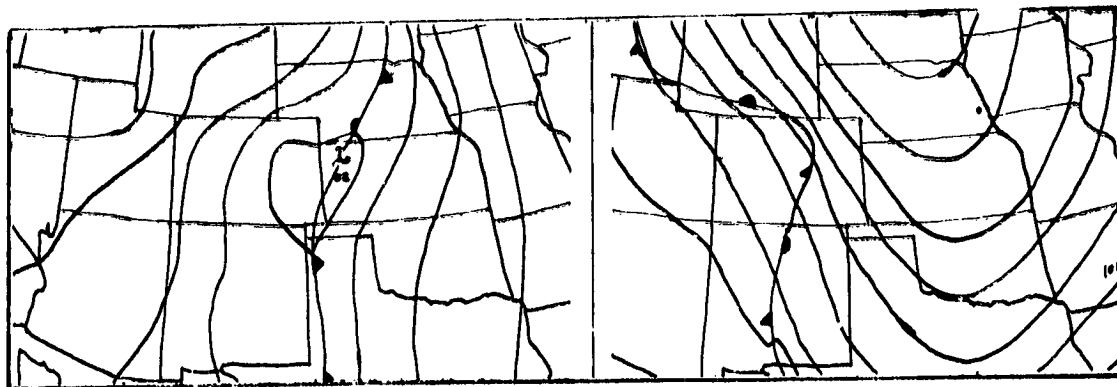


FIGURE 5. TYPICAL SURFACE MAP DESCRIPTION ASSOCIATED WITH STRONG WIND (LEFT) AND WEAK WIND (RIGHT) FOR CLAYTON.

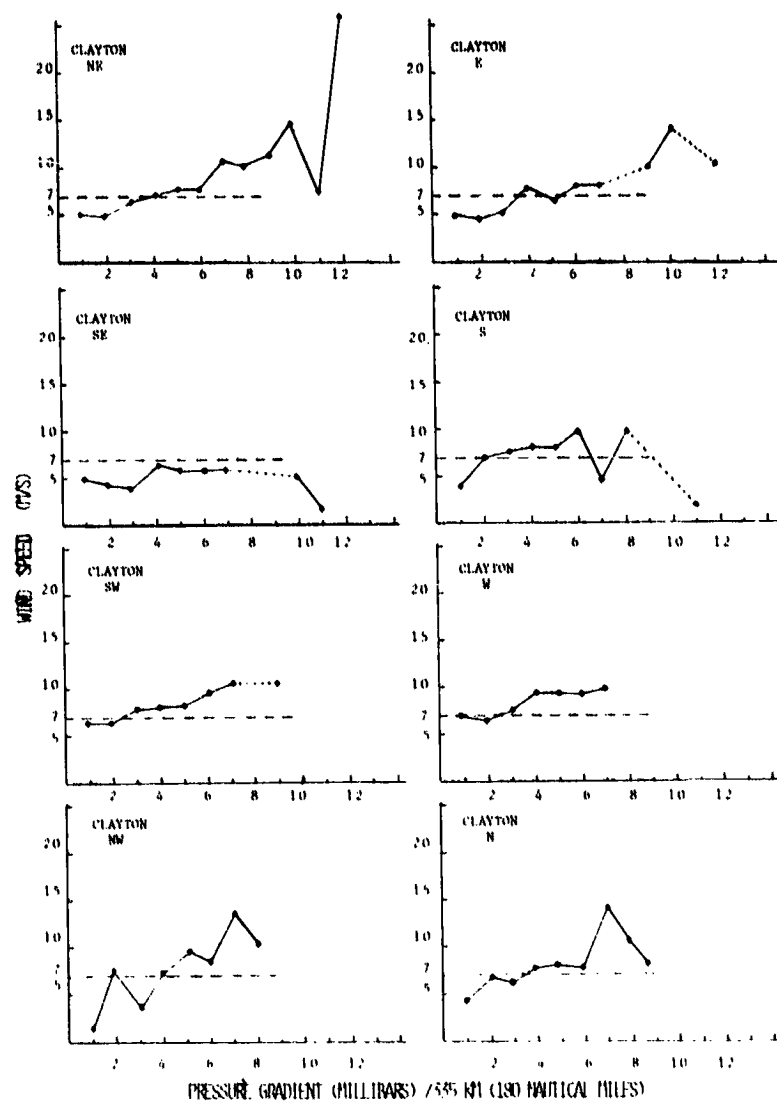


FIGURE 6. SAME AS FIGURE 4 EXCEPT THESE CURVES FOR CLAYTON.



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1. A NE gradient generally results in 300°-350° direction and >10 m/s if gradient is >5mb.
2. Speeds can be often light with NE gradient unless the pressure gradient is strong or is under the influence of strong "post front" type.
3. An E gradient of <3mb results in variable direction and <7m/s
4. A SE gradient yields winds of <7m/s often blowing 02°-08°.
5. If high ridges southward into the site the direction will be 130°-150° with a SE gradient.
6. For a S gradient speeds are generally >7m/s even for very weak gradients (2mb in 180 nautical miles). Direction is generally 160°-220° depending on the low position.
7. For a SW gradient, if trough is near the site, speed will be quite strong (>7m/s) from the S or SW regardless of gradient strength.
8. With a W gradient, speed is generally >7m/s from 180° to 220°.
9. With a NW gradient wind blows 270°-300° if no low pressure is in the vicinity. If a low is located northeast of Clayton, the wind will blow from about 240°.

Boone

This site is located on top of a 1348m (4420 ft.) mountain in far western North Carolina on the Appalachian Chain. The statistics of Table 5 show the most common B-A types to be 3-5 and 29-35. The direction with the stronger speeds are SW through NW with the peak speeds occurring with NW winds as is common in the eastern U.S. At Boone the super strong winds (occasionally >20m/s) occur as a low passes off to the north, the associated strong cold front pushes east of the site, and the high pressure center approaches from the middle part of the country. The B-A synoptic types with that regime are 3, 29, and 31. These types are naturally more predominant in the winter half of the year. From Table

TABLE 5. WIND STATISTICS FOR BOONE

CLASS No.	No. of Obs.	SURFACE				BOONE				Surface to 850 Ratio
		Average Direction	Average Speed	Average Sigma	Average Direction	Average Speed	Average Sigma	Average Direction	Average Speed	
1	16	231	58	8.0	3.1	75	230	17	11.6	1.00
2	64	107	27	11.9	5.1	90	267	19	14.1	0.18
3	16	227	47	8.3	3.8	60	277	17	17.3	0.03
4	19	230	29	10.1	3.9	80	276	16	14.9	0.78
5	4									
6	1									
7	1									
8	1									
9	1									
10	2									
11	9	355	48	9.7	2.8	89	234	27	13.1	1.10
12	12	322	38	9.0	4.7	80	261	16	11.9	0.50
13	11									
14	8									
15	7									
16	7									
17	10	233	27	10.0	3.6	60	273	11	11.8	0.70
18	1	238	30	9.0	3.0	6	232	14	11.0	0.7
19	1	233	24	12.5	3.7	93	277	18	11.8	0.6
20	7									
21	1									
22	1	196	80	11.8	3.1		275	29	8.0	1
23	1									
24	1									
25	1	190	30	10.0	3.0	14	231	87	11.1	1.800
26	4	200	20	10.3	3.0	68	230	16	11.4	0.68
27	1	233	30	10.1	3.0	11	267	14	8.7	0.7
28	10	230	27	10.3	3.7	80	277	13	9.3	0.8
29	63	31	30	10.0	5.5	90	193	11	11.6	0.10
30	1	230	30	9.6	3.0	11	233	11	10.3	1.700
31	1	230	30	8.0	3.0	11	233	11	11.3	0.70
32	16	230	30	9.0	3.0	11	230	11	11.3	0.7
33	1	230	30	9.0	3.0	11	230	11	11.3	0.7
34	1	230	30	9.0	3.0	11	230	11	11.3	0.7
35	1	230	30	9.0	3.0	11	230	11	11.3	0.7

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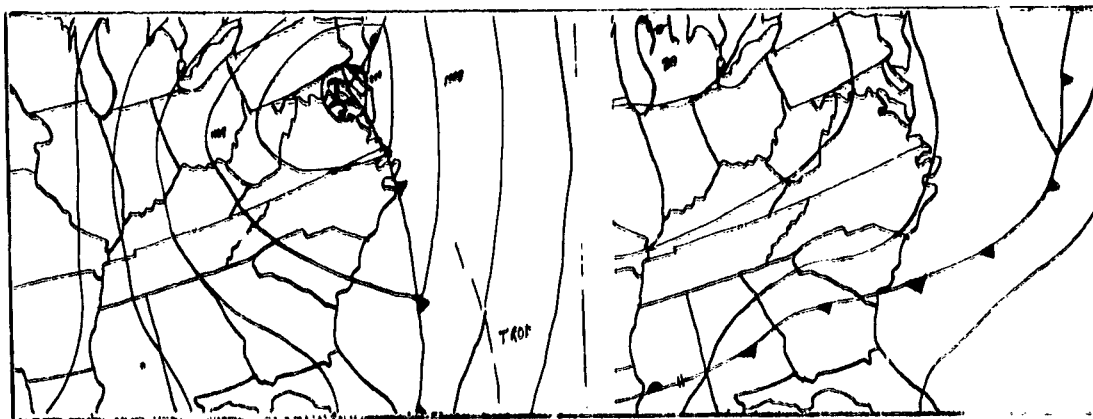


FIGURE 7. TYPICAL SURFACE MAP DESCRIPTION ASSOCIATED WITH STRONG WIND (LEFT) AND WEAK WIND (RIGHT) FOR BOONE.

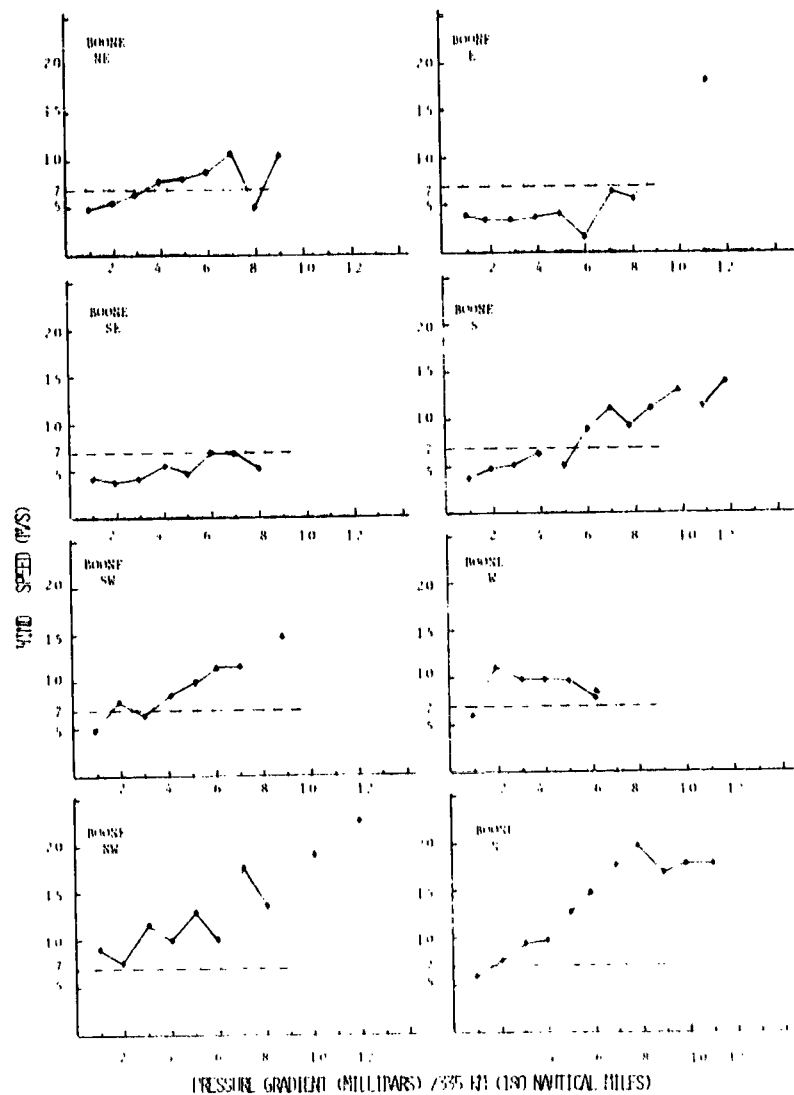


FIGURE 8. SAME AS FIGURE 4 EXCEPT THESE CURVES FOR BOONE

5, the surface to 850-mb speed ratios are generally between 0.7 and 0.9 for the common B-A types. The exception is B-A number 30 having a ratio of about 1.2. The strong wind B-A types also have high percentage values of  $\geq 7$  m/s. Typical strong and weak synoptic types for Boone are shown in Figure 7.

On Figure 8 it is seen that the only gradients resulting in very light wind are the E and SE and in some respects the NE and S with gradient strength  $< 4$  mb. The dashed lines in some of these curves indicate lack of data between points. The SW and N gradients result in strong wind events as seen in the graphs.

A few "rules of thumb" for Boone include the following for the NE through S gradients (tricky gradients for this site):

1. With a NE gradient, direction is generally  $320^\circ - 340^\circ$  except with an E to W high pressure to the north or a low to the S or SE in which case the direction is  $010^\circ - 040^\circ$ . Speeds are generally fairly strong if gradient strength is  $\geq 4$  mb.
2. The direction with an E light gradient is  $300^\circ - 330^\circ$ . Stronger gradients result in  $070^\circ - 110^\circ$  wind direction. In just about all cases the speed is rarely over 5 or 6 m/s.
3. The SE gradient results in light speed (generally  $< 6$  m/s) and often has  $290^\circ - 330^\circ$  direction.
4. With a weak S gradient ( $\leq 4$  mb) wind tends to blow with the S gradient direction and be  $\leq 7$  m/s. When a wave or trough passes through the vicinity of Tennessee-Kentucky area a SE direction will result. If gradient is strong, wind will blow with the gradient. The speed is quite strong ( $> 10$  m/s) when a front is near the site with the S gradient.

#### Montauk

This site is located on the southeastern tip of Long Island, N.Y. The most common synoptic types for this site are B-A numbers 2-5, 18-19, 29-35 as seen in Table 6. Because of its location in the northeastern U.S., it is affected by quite a few synoptic types. This is not necessarily the case for San Geronio, Clayton, and in some respects Boone. The table shows the strongest speeds tending to be associated with B-A types having W or NW winds. About the only apparent contradiction to this is B-A type 31 with mean speed of 6.5 m/s. This type has a large number of occurrences (119) but it is also noted that the  $\sigma$  is astronomical. Thus, in many of these cases it is suspected that the ridge axis is just west with the high center to the north. This can cause a considerable number of cases with light E through NW winds explaining the rather low speed for B-A number 31. The surface to 850-mb ratio is generally between 0.4 and 0.7 for the common synoptic types. This ratio is significantly lower than the ratio for the other sites, but on the other hand the 850-mb speed is stronger for this site as is common for the northeast U.S. Figure 9 shows the typical strong wind and weak wind pattern for Montauk.

Glancing at Figure 10 for Montauk, one thing that should be pointed out is that it generally takes  $\geq 4$  mb gradient strength for all gradient directions to result in speeds of  $\geq 7$  m/s. The gradients with the

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MONTAUK									
Class No.	No. of obs.	Surface		Average		% $\geq 7$ m/s	Average		Surface to 850 mb
		Direction	Speed	Direction	Speed				
1	4								
2	19	151	61	6.7	1.0	42	214	29	15.4
3	84	167	52	9.1	4.4	21	292	18	14.2
4	24	195	15	7.1	2.9	61	226	17	15.2
5	59	201	68	6.5	1.6	11	210	46	19.8
6	8	101	51	10.4	1.7	88	171	13	20.0
7	10	101	75	9.4	2.8	89	171	69	14.8
8	14	117	49	6.7	1.1	57	258	104	9.8
9	14	---	---	---	---	---	---	---	---
10	1	---	---	---	---	---	---	---	---
11	2	---	---	---	---	---	---	---	---
12	7	247	41	1.9	2.5	14	261	40	9.9
13	8	---	---	5.2	4.4	25	---	---	9.7
14	12	164	62	4.0	2.5	17	218	62	7.1
15	6	---	---	4.1	1.6	0	---	---	9.5
16	4	---	---	---	---	---	---	---	---
17	9	210	51	5.5	2.7	13	240	31	12.0
18	21	204	66	6.4	2.4	51	228	10	12.2
19	20	110	52	9.7	2.3	62	276	51	10.1
20	1	---	---	---	---	---	---	---	---
21	10	81	45	8.4	2.7	84	168	17	8.4
22	4	---	---	---	---	---	---	---	---
23	2	---	---	---	---	---	---	---	---
24	12	227	41	7.2	1.7	45	272	39	11.5
25	14	293	48	7.5	5.7	45	275	67	9.0
26	10	276	47	6.5	1.6	50	276	55	11.8
27	0	---	---	---	---	---	---	---	---
28	1	---	---	---	---	---	---	---	---
29	73	299	43	8.5	4.2	64	304	26	15.1
30	86	211	44	6.2	2.8	42	249	34	10.4
31	119	292	106	6.5	1.7	48	---	---	10.5
32	184	114	---	1.2	2.1	6	---	---	6.1
33	80	152	65	4.8	2.5	25	231	50	8.2
34	28	46	20	7.6	2.5	63	115	78	6.0
35	12	187	77	3.8	2.5	15	245	49	5.1

weaker speeds seem to be NE, E, and S but note the large range for this site. The gradients associated with the highest speeds are the NW and N.

The "rules of thumb" observed for this site include the following:

1. NE gradient is not generally good for strong wind. A high percentage of cases are  $< 7$  m/s. This is especially true for gradients  $< 7$  mb.
2. E gradient is likewise not a strong wind gradient but is a bit stronger than NE. A gradient strength 3 or 4 mb usually produces wind of  $\geq 7$  m/s.
3. SE gradient is not very frequent. For a gradient strength of  $> 3$  mb the speed is  $\geq 7$  m/s.
4. S gradient is not a strong wind gradient. It usually takes  $\geq 5$  mb to result in wind of  $\geq 7$  m/s.
5. SW gradient is fairly common. 4mb or higher gradient gives wind of  $\geq 7$  m/s but even smaller gradient strength can result in quite a few cases of  $\geq 7$ .
6. The W gradient is also common. Any gradient can produce wind of  $\geq 7$  m/s but gradients of  $> 5$  mb results in speed  $\geq 7$  consistently.
7. The NW gradient produces some of the strongest winds of up to 20 m/s consistently.
8. The N gradient also produces speeds up to 20 m/s and a lot in the range of 10-20 m/s. A strength  $\geq 5$  mb results in speed of  $\geq 7$  m/s consistently.
9. Of the four sites studied Montauk by far has the best correlation between wind direction and gradient. The direction is generally within  $10^\circ$ - $30^\circ$  of the gradient direction.

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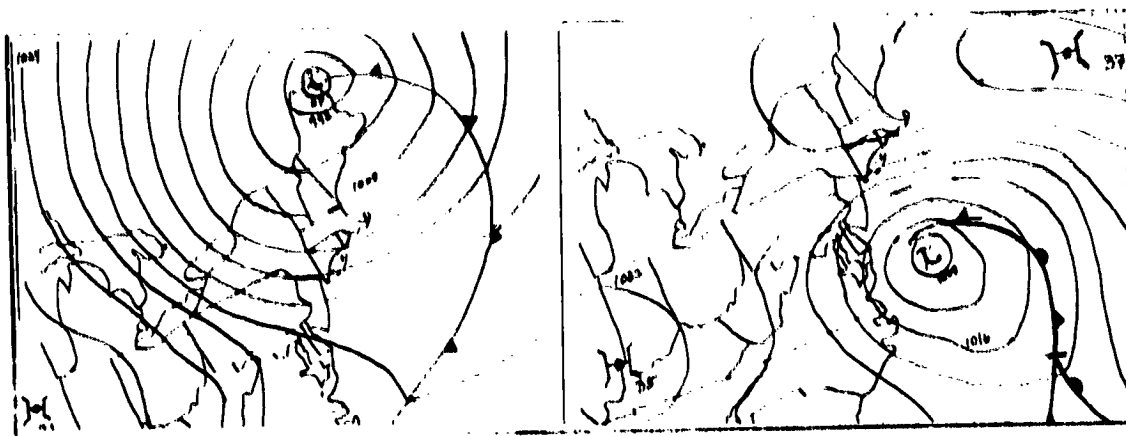


FIGURE 9. TYPICAL SURFACE MAP DESCRIPTION ASSOCIATED WITH STRONG WIND (LEFT) AND WEAK WIND (RIGHT) FOR BOONE.

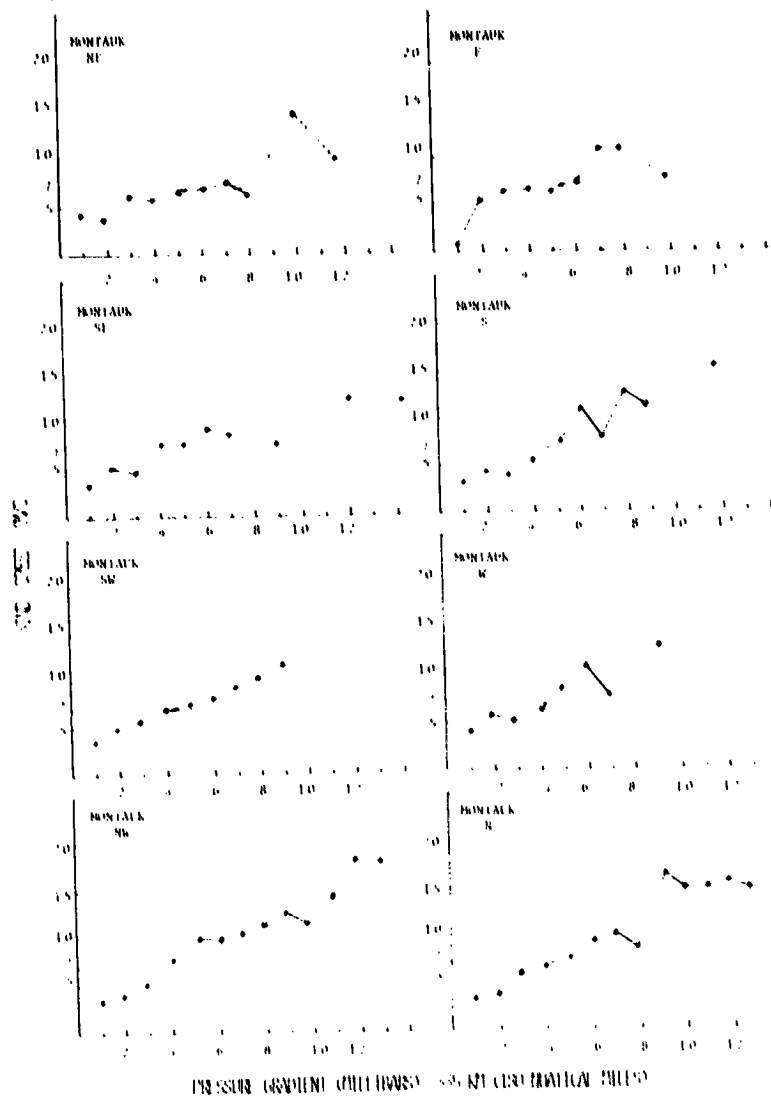


FIGURE 10. SAME AS FIGURE 4 EXCEPT THESE CURVES FOR MONTAUK.

## SUMMARY

Research on this project is by no means complete, but the results and findings to this point are very encouraging. There are strong correlations between synoptic features and wind events. The wind events are obviously also influenced by the local topography. When this study began, there were three major questions to be answered:

1. Are there synoptic or subsynoptic scale weather patterns evident at the sites in such a recognizable pattern, that they can be used to more accurately predict wind events for the purposes of power generation?
2. Given a set of criteria with unique characteristics, can one then recognize the weather patterns with which they are associated?
3. Using the site winds and archived analyses, can characterization of the site winds in terms of apparent mesoscale effects of local topography be separated from synoptic scale effects?

The answers to all of these are positive. The results clearly show that by using existing data for a given site, the winds can be characterized and correlated with synoptic weather patterns. When this is accomplished, there is no doubt that forecasts of wind events for the large wind power generators will be quite reliable and very useful to utility companies. If given the opportunity to once again forecast for these sites following the completion of this research, the author strongly believes that these forecasts will be much more accurate, than those during the forecasting project of 1979.

As previously mentioned the current research is not complete. More work is needed to study in greater detail diurnal and seasonal effects. Further investigation is also necessary on gradient, speed, and direction relations. Finally, some refinement of the findings is also needed.

## ACKNOWLEDGMENTS

The author is greatly indebted to Alan H. Miller and Harry Wegley of Battelle, Northwest Laboratories for their tremendous assistance in this project. The effort of Freese-Notis Weather meteorologists, Dan Hicks, Miles Schumacher, and Ryan Tilley, who devoted many hundreds of hours in research for this project, is much appreciated.

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# ATMOSPHERIC TURBULENCE PARAMETERS FOR MODELING WIND TURBINE DYNAMICS

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## ABSTRACT

This paper presents a model which can be used to predict the response of wind turbines to atmospheric turbulence. The model was developed using linearized aerodynamics for a three-bladed rotor and accounts for three turbulent velocity components as well as velocity gradients across the rotor disk. Typical response power spectral densities are shown. The system response depends critically on three wind and turbulence parameters, and models are presented to predict desired response statistics. An equation error method, which can be used to estimate the required parameters from field data, is also presented.

## WIND TURBINE SYSTEM MODEL

Before embarking on a discussion of the detailed characteristics of atmospheric turbulence parameters, it is necessary to present the modeling framework in which the parameters will be used to predict system responses. The primary purpose of the model is to provide a tool by which designers can estimate the effects of fluctuating turbulence inputs on the wind turbine, structural and power system responses.

For an  $n$  degree of freedom system, the basic principles of Newtonian mechanics [1] give equations of motion of the form

$$[M]\{\ddot{z}\} + [C_s]\{\dot{z}\} + [K_s]\{z\} = \{f_a\} \quad (1)$$

where  $\{z\}$  = the  $n \times 1$  vector of generalized displacement coordinates.  
 $[M]$  = the  $n \times n$  inertia matrix.  
 $[C_s]$  = the  $n \times n$  gyroscopic and structural and power train damping matrix.

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$[K]$  = the nxn structural and power train stiffness matrix.  
 $\{f_a^s\}$  = the nx1 vector of aerodynamic forces and moments generated by the turbine rotor.

The aerodynamic forcing term of Eq. (1) depends upon the motion of the turbine rotor with respect to the ground as well as the motion of the air. If the aerodynamic forces and moments are linearized about a steady operating condition, the following equation results

$$\{f_a\} = \{f_n\} + [F]\{u\} - [C_a]\{\dot{z}\} - [K_a]\{z\} \quad (2)$$

where  $\{f_n\}$  = the nx1 vector of steady, nominal aerodynamic forces and moments.  
 $\{u\}$  = the mx1 vector of fluctuating turbulence inputs.  
 $[F]$  = the nxm matrix of aerodynamic influence coefficients.  
 $[C_a]$  = the nxn aerodynamic damping matrix.  
 $[K_a]$  = the nxn aerodynamic stiffness matrix.

In this particular model, the turbulence input vector  $\{u\}$  consists of three velocity components which are uniform over the turbine rotor disk and six additional gradient terms which account for variations in turbulent velocity over the rotor disk. Table 1 gives a verbal description of the nine turbulence input terms appropriate for a rigid, three-bladed wind turbine rotor.

TABLE 1. DESCRIPTION OF TURBULENCE INPUT TERMS

Component	Description
$V_x$	uniform lateral or side component (in rotor plane)
$V_y$	uniform longitudinal component along steady wind direction
$V_z$	uniform vertical component (in plane)
$V_{y,x}$	lateral gradient of longitudinal velocity
$V_{y,z}$	vertical gradient of longitudinal velocity
$\gamma_{xz}$	swirl about steady wind axis (in plane)
$\left. \begin{matrix} \epsilon_r \\ -\gamma_r \end{matrix} \right\}$	shear strain rates (in plane) expressed in a reference frame rotating at three times the rotor rate
$\bar{\epsilon}_{xz}$	in-plane dilation



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Assuming that the atmospheric turbulence is adequately described by the homogeneous, isotropic Von Karman model [2], the turbulence input vector can be approximated by the following set of stochastic differential equations [3]

$$\dot{\{u\}} = [A_w]\{u\} + [B_w]\{w\} \quad (3)$$

where  $\{w\}$  = an  $m \times 1$  vector of white noise excitations with flat power spectral density,  $S_w = \sigma^2 L / V_w^3$ .  
 $[A_w]$  = the  $m \times m$  dynamics matrix for the turbulence inputs.  
 $[B_w]$  = the  $m \times m$  distribution matrix for the white noise excitations.

The matrices  $[A_w]$  and  $[B_w]$  are diagonal, except for two off diagonal terms in  $[A_w]$ , which account for the three rotations per rotor revolution effect in the  $c_r$  and  $\bar{\gamma}_r$  terms caused by the three blades moving through the in-plane turbulence gradients.

The motion Eqs. (1), the aerodynamic force Eqs. (2), and the wind turbulence inputs Eqs. (3) can be combined into a set of system equations of the form

$$\begin{aligned} \dot{\{x\}} &= [A]\{x\} + [B]\{w\} \\ \{y\} &= [C]\{x\} + \{y_n\} \end{aligned} \quad (4)$$

where

$$\begin{aligned} \{x\} &= \begin{Bmatrix} \delta z \\ \delta \dot{z} \\ u \end{Bmatrix} \quad \text{the } N \times 1 \text{ system state vector } (N = 2n+m) \\ \{w\} &= \text{the } m \times 1 \text{ white noise turbulence excitation vector.} \\ \{y\} &= \text{the } l \times 1 \text{ vector of system response variables.} \\ \{y_n\} &= \text{the } l \times 1 \text{ vector of steady nominal system responses.} \\ [A] &= \begin{bmatrix} 0 & I & 0 \\ -M^{-1}(K_s + K_a) & -M^{-1}(C_s + C_a) & M^{-1}F \\ 0 & 0 & A_w \end{bmatrix} = \text{the } N \times N \text{ system matrix} \\ [B] &= \begin{bmatrix} 0 \\ 0 \\ B_w \end{bmatrix} = \text{the } N \times m \text{ white noise excitation distribution matrix.} \\ [C] &= \text{the } l \times N \text{ response distribution matrix.} \end{aligned}$$

Note that  $\delta z$  and  $\delta \dot{z}$  are deviations from the steady, generalized displacement and velocity components. The outputs  $\{y\}$  and the corresponding matrix  $[C]$  depend upon the particular set of displacements, velocities or load response variables of interest to the designer.

The system equations of motion given by Eq. (4) are derived assuming a rigid, three-bladed turbine rotor. It is possible to derive system equations for two-bladed rotors similar to these equations, except that several of the terms in the  $[A]$  matrix will have periodic terms

instead of being constant as in Eq. (4).

At this point, we will describe briefly how the wind parameters enter the various coefficients of the overall system model. First, the steady wind speed,  $V_w$ , affects the nominal aerodynamic forces and the linearized aerodynamic coefficients in the matrices  $[C_a]$ ,  $[K_a]$  and  $[F]$ . Second, both the steady wind speed,  $V_w$ , and the turbulence integral scale,  $L$ , affect the matrices  $[A_w]$  and  $[B_w]$ . Finally, the turbulence component variance,  $\sigma^2$ , as well as  $V_w$  and  $L$ , affect the power spectral density,  $S_w$ , for each of the white noise excitation components. Thus, three atmospheric turbulence parameters,  $V_w$ ,  $\sigma$ , and  $L$ , must be known in order to utilize the model given by Eq. (4).

Once the appropriate turbulence parameters are specified, the response, power spectral densities can be computed using the model given by Eq. (4). Since the white noise inputs are uncorrelated, the following equation results

$$\{S_y(\omega)\} = [T(\omega)]\{S_w\} \quad (5)$$

where  $\{S_y(\omega)\}$  = the  $l \times 1$  vector of response power spectral densities.  
 $\{S_w\}$  = the  $m \times 1$  vector of white noise excitation power spectral densities.  
 $[T(\omega)]$  = the  $l \times m$  matrix of squared, complex magnitudes of the system frequency response matrix elements.  
 $\omega$  = the radian frequency.

If  $T_{jk}(\omega)$  is one element of  $[T(\omega)]$ , then

$$T_{jk}(\omega) = |H_{jk}(i\omega)|^2 \quad (6)$$

where  $H_{jk}(i\omega)$  = the corresponding element of the complex frequency response matrix.  
 $i$  =  $\sqrt{-1}$ .

Assuming the eigenvalues of the system dynamics matrix  $[A]$  are distinct, the complex frequency response matrix is given by

$$[H(i\omega)] = [C][M][i\omega[I] - [A]]^{-1}[B] \quad (7)$$

where  $[M]$  = complex modal matrix consisting of columns of eigenvectors of  $[A]$ .  
 $[A]$  = diagonal complex matrix of eigenvalues of  $[A]$ .  
 $[I]$  = identity matrix.

# TYPICAL WIND TURBINE RESPONSE CHARACTERISTICS

A simplified five-degree-of-freedom model for a three-bladed, horizontal-axis wind turbine was developed by Thresher, et al. [4]. The five generalized displacement degrees of freedom are given by

$$\{z\}^T = (U, V, \phi, \chi, \psi) \quad (8)$$

where  $U$  = lateral displacement of the nacelle in x direction.  
 $V$  = fore-aft displacement of the nacelle in y direction.  
 $\phi$  = yaw angle.  
 $\chi$  = pitch angle.  
 $\psi$  = rotor angular displacement about spin axis.

Figure 1 shows the coordinate system used for this model. The configuration shown in the figure is appropriate for a down-wind rotor design.

Thresher and Holley [5] utilized the model for two typical wind turbines of widely differing size. The first, designated the Mod-M, is an 8 kW free yaw system with a down-wind rotor. The second, the Mod-G, is a large 2.5 MW machine with a fixed yaw, up-wind rotor. The system characteristics for these two machines are given in Tables 2 and 3.

TABLE 2. MOD-M CHARACTERISTICS

## Rotor Characteristics:

Rotor Radius	5.081 m	(16.67 ft)
Hub Height	16.8 m	(55 ft)
Blade Chord (constant)	.457 m	( 1.5 ft)
Coning Angle	.061 rad	( 3.5°)
Blade Twist	0 rad	( 0.0°)
Pitch Setting (to ZLL)	.052 rad	( 3.0°)

## Steady Operating Conditions:

Rotor Speed, $\Omega$	7.681 rad/s	(73.35 RPM)
Wind Speed, $V_w$	7.434 m/s	(16.63 MPH)
Approximate Output	6 kW	

## Aerodynamic Properties:

Lift Curve Slope	5.7
Drag Coefficient $C_{D0}$	.02

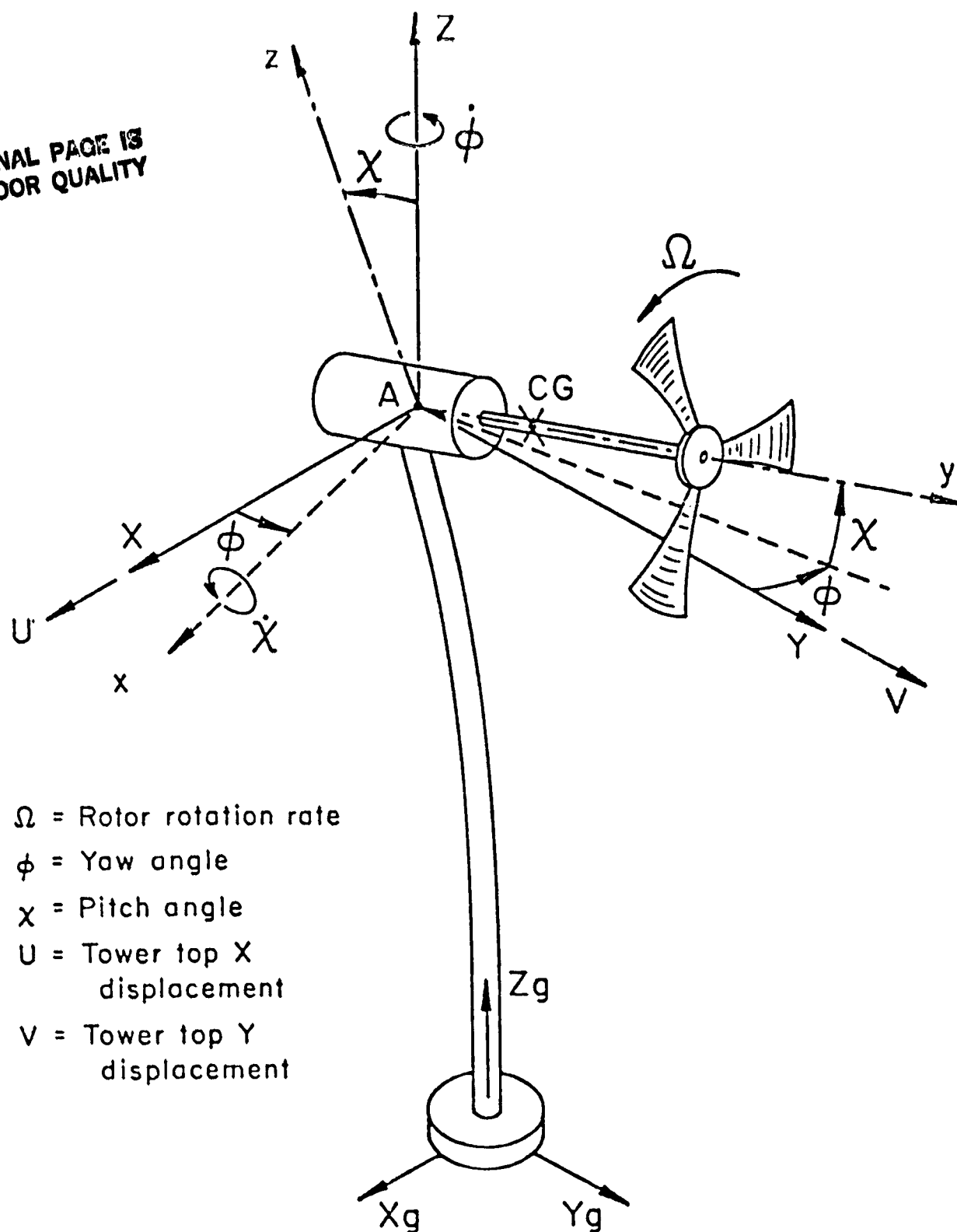
## Turbulence Parameters:

Standard Deviation, $\sigma$	.619 m/s	( 2.03 ft/s)
Integral Length Scale, $L$	91.44 m	(300 ft )

## System Frequencies (Tower Motion):

1st Bending (fore-aft)	15.1 rad/s	(2.0 $\Omega$ )
2nd Bending (fore-aft)	53.1 rad/s	(7.0 $\Omega$ )
1st Bending (side-to-side)	15.9 rad/s	(2.1 $\Omega$ )
1st Torsion	0.0 rad/s	(Free Yaw)

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$\Omega$  = Rotor rotation rate  
 $\phi$  = Yaw angle  
 $\chi$  = Pitch angle  
 $U$  = Tower top  $X$   
displacement  
 $V$  = Tower top  $Y$   
displacement

Figure 1. Coordinate Definitions for the Wind Turbine Model.

TABLE 3. MOD-G CHARACTERISTICS

<u>Rotor Characteristics:</u>		
Rotor Radius	45.7 m	(150 ft)
Hub Height	61.0 m	(200 ft)
Blade Chord (linear taper)	2.36 m	( 7.74 ft)
	to .96 m	to 3.15 ft)
Coning Angle	.070 rad	( 4.0°)
Blade Twist (linear)	.140 rad	( 8.0°)
Pitch Setting at Tip (to ZLL)	.108 rad	( -6.2°)
<u>Steady Operating Conditions:</u>		
Rotor Speed, $\Omega$	1.833 rad/s	( 17.5 RPM)
Wind Speed, $V_w$	8.940 m/s	( 20.0 MPH)
Approximate Output	1.1 MW	
<u>Aerodynamic Properties:</u>		
Lift Curve Slope	5.73	
Drag Coefficient, $C_{D0}$	.008	
<u>Turbulence Parameters:</u>		
Standard Deviation, $\sigma$	.744 m/s	( 2.44 ft/s)
Integral Length Scale, L	152.4 m	(500 ft )
<u>System Frequencies (Tower Motion):</u>		
1st Bending (fore-aft)	2.75 rad/s	( 1.5 $\Omega$ )
2nd Bending (fore-aft)	12.8 rad/s	( 7.0 $\Omega$ )
1st Bending (side-to-side)	2.9 rad/s	( 1.6 $\Omega$ )
1st Torsion	9.5 rad/s	( 5.2 $\Omega$ )

Two aerodynamic wake models were used for each system to compute the coefficients in the aerodynamic system matrices  $[C_a]$ ,  $[K_a]$ , and  $[F]$ . In the first, the steady conditions are used with standard momentum theory to compute the steady distribution of induced velocity across the rotor disk. This induced velocity is then assumed constant for the given conditions. This model is called the "Frozen Wake." In the second model, the induced velocity which results from a slowly varying velocity field is computed using a quasi-steady momentum balance. In this model, the turbine thrust is always in equilibrium with the driving turbulent velocity, and is called the "Equilibrium Wake." Aerodynamic stall is not modeled in either case.

Figures 2 and 3 show the power spectral densities of the thrust load and the yaw angle for the Mod-M machine. In the low frequency portion of Figure 2, the thrust load response closely follows the power spectrum of the  $V_y$  turbulence input. At higher frequencies the resonance effects of the tower bending modes are observed. In Figure 3, the yaw response is dominated by the  $V_{y,x}$  turbulence input. This turbulence input term can be interpreted as the rate of change of the direction in the horizontal turbulent velocity component. A smaller additional effect is due to the uniform side velocity,  $V_x$ , turbulence term.

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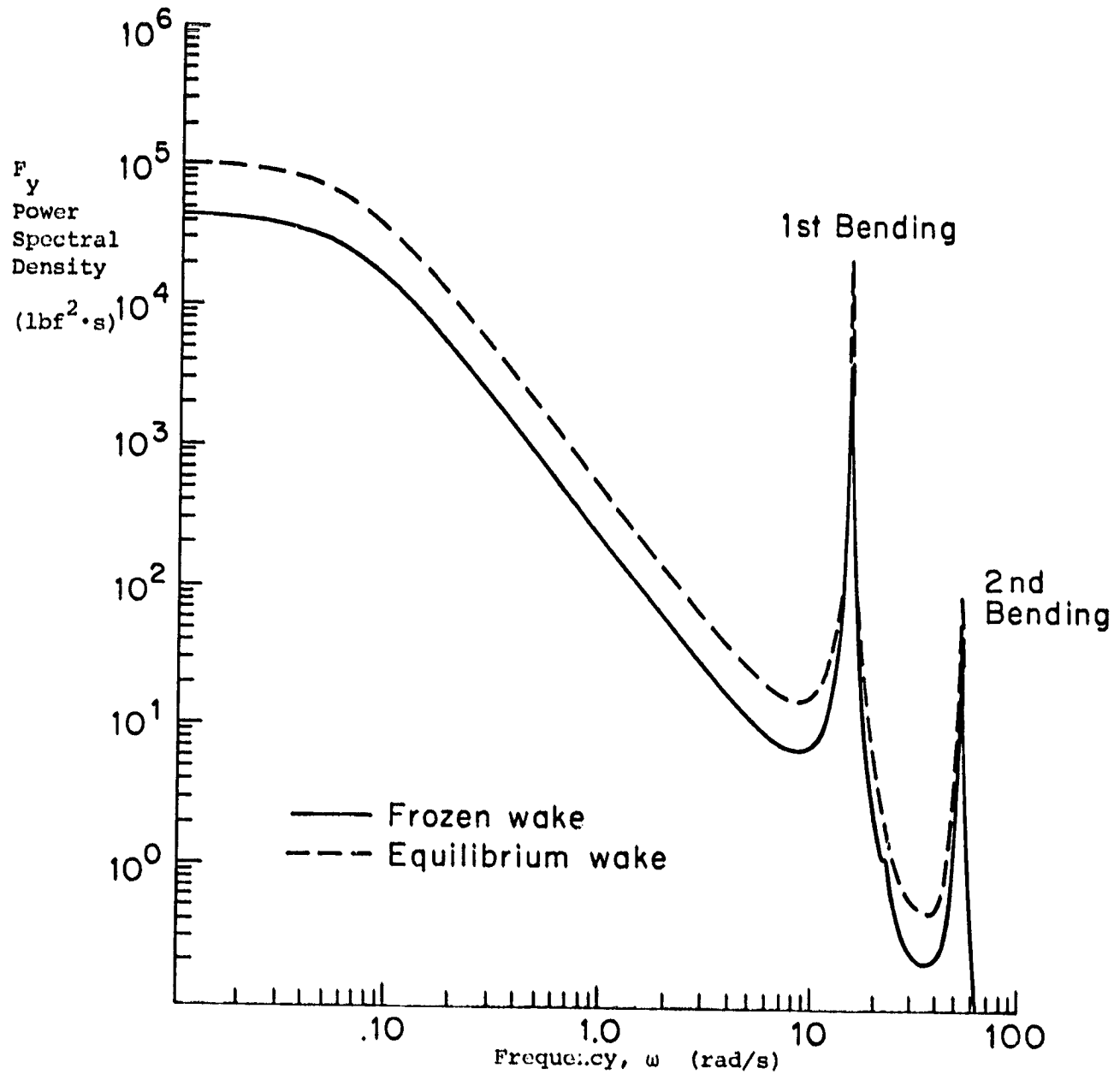


Figure 2. Thrust Load,  $F_y$ , for Mod-M.

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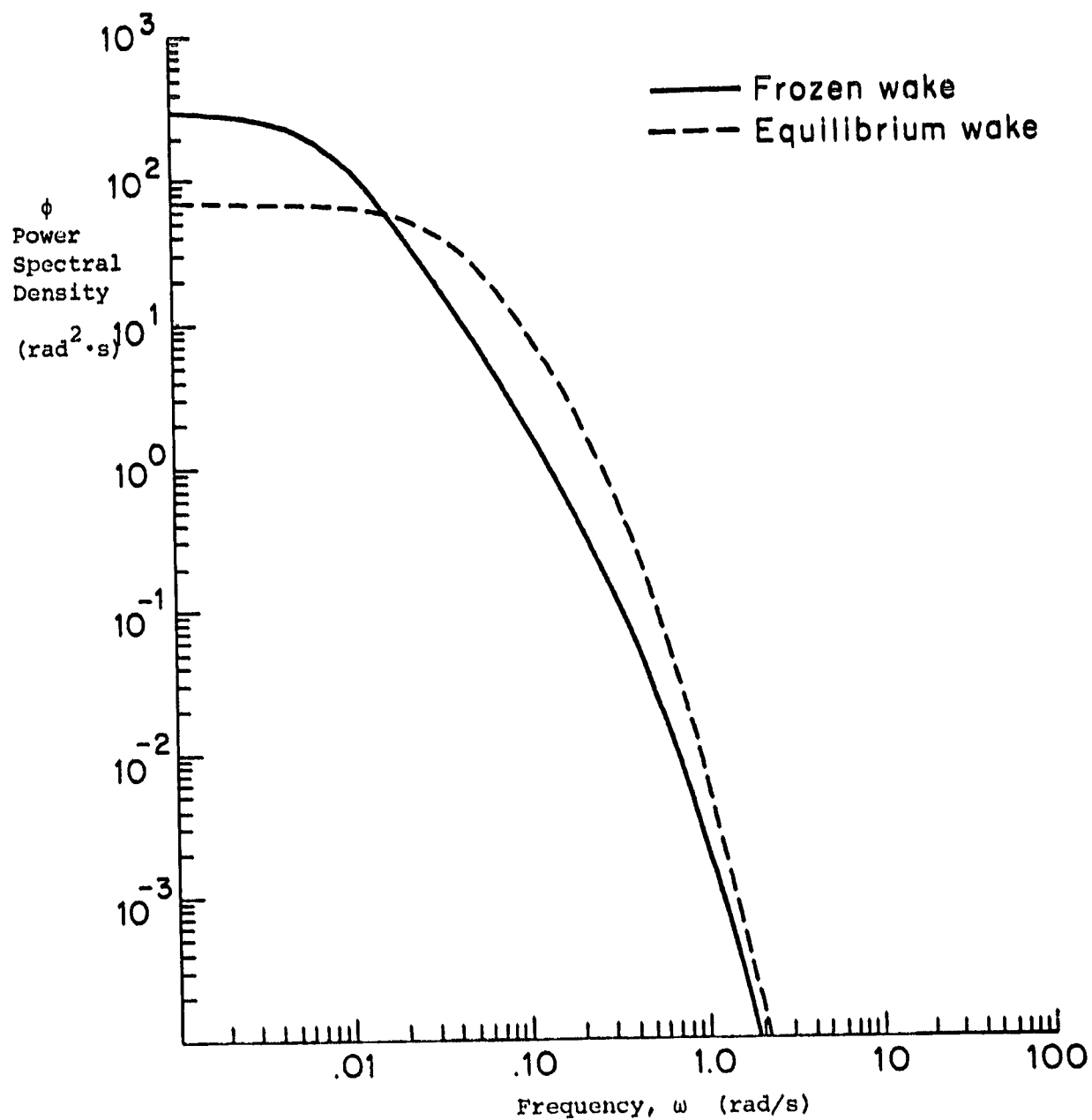


Figure 3. Yaw Response,  $\phi$ , for Mod-M.

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Figures 4 and 5 show similar results for the Mod-G machine except that the tower torsion load is shown instead of the yaw angle for this fixed yaw machine. The Mod-G machine shows a greater sensitivity to the 30 effects of the  $c_x$  and  $\gamma_x$  turbulence terms.

## METHODOLOGY FOR COMPUTATION OF RESPONSE STATISTICS

This section gives a brief discussion of the techniques by which the model given by Eq. (4) can be used to compute desired response statistics. Assuming that the fluctuating components of the atmospheric turbulence are adequately described by Gaussian statistics [6,7], the model will give the conditional probability density function of the response given the steady wind speed  $V_w$ , and the turbulence parameters  $\sigma$  and  $L$ . Thus, considering only a single, scalar response variable

$$p(y|V_w, \sigma, L) = \frac{1}{\sigma_y \sqrt{2\pi}} e^{-1/2(y - \mu_y / \sigma_y)^2} \quad (9)$$

where  $\mu_y = y_n(V_w)$  = the steady response for given  $V_w$   
 $\sigma_y = \sigma_y(V_w, \sigma, L)$  = the rms response for given  $V_w$ ,  $\sigma$ , and  $L$ .

This function can be recognized as the standard Gaussian density function. The conditional mean,  $\mu_y$ , is a nonlinear function of  $V_w$ , and the conditional rms response,  $\sigma_y$ , depends nonlinearly on  $V_w$  and  $L$  and is proportional to  $\sigma$ . The rms response,  $\sigma_y$ , can be computed from the response power spectral density by the relation

$$\sigma_y^2 = \frac{1}{\pi} \int_0^\infty S_y(\omega) d\omega \quad (10)$$

The response variance  $\sigma_y^2$  can also be calculated directly using the relation [8]

$$\sigma_y^2 = [C] [M] [P] [M]^* [C]^T \quad (11)$$

where  $[C]$  = the row matrix relating the response to the system state vector.  
 $[M]$  = modal matrix with column eigenvectors.  
 $*$  = complex conjugate of the matrix.

The Hermitian matrix,  $[P]$ , satisfies the linear relation

$$[\Lambda] [P] + [P] [\Lambda]^* + [M]^{-1} [B] [B]^T [M]^{-*T} \left( \frac{\sigma^2 L}{V_w^3} \right) = 0 \quad (12)$$

where  $[\Lambda]$  = the diagonal matrix of complex eigenvalues.  
 $[B]$  = the white noise input distribution matrix.



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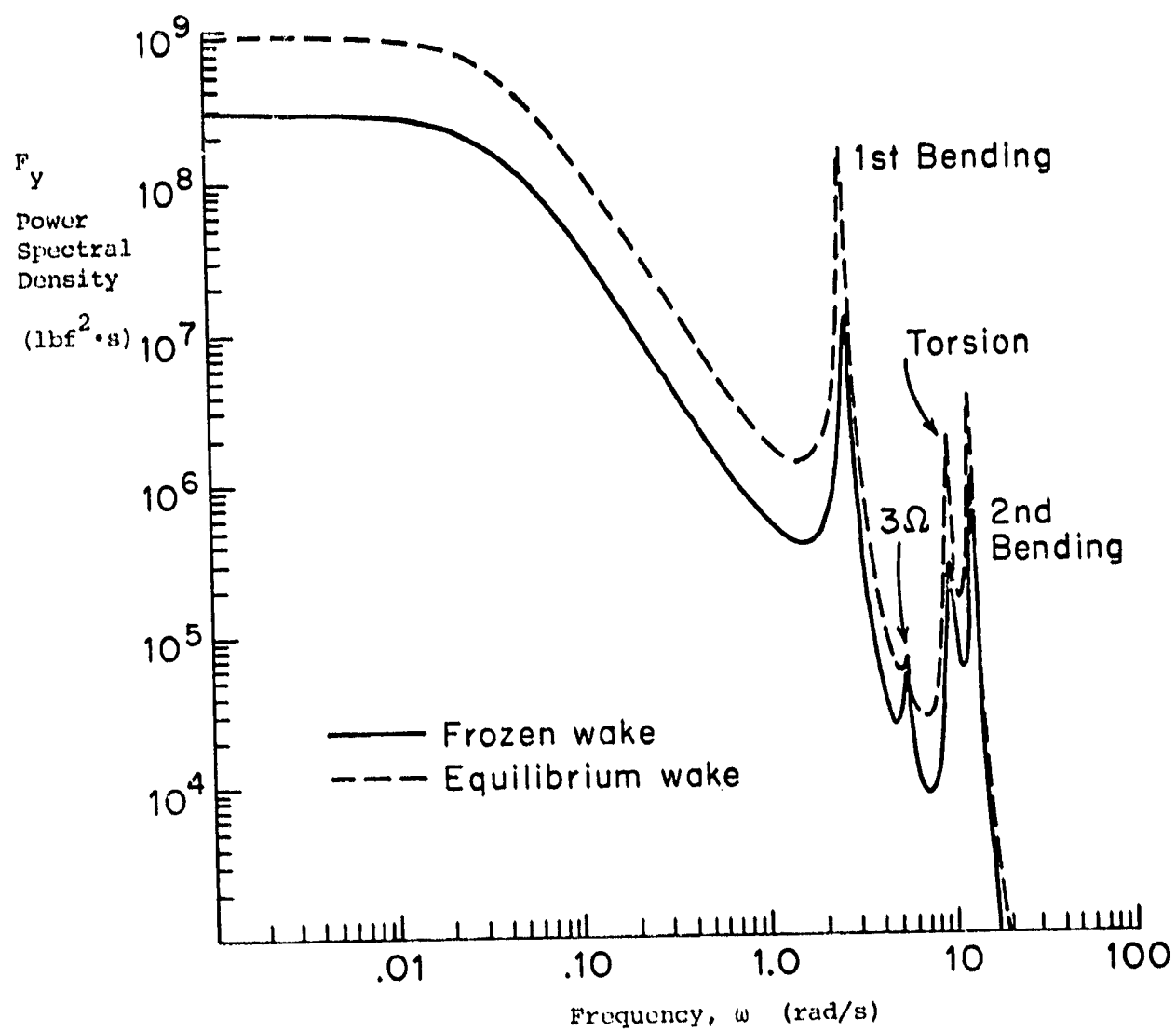


Figure 4. Thrust Load,  $F_y$ , for Mod-G.

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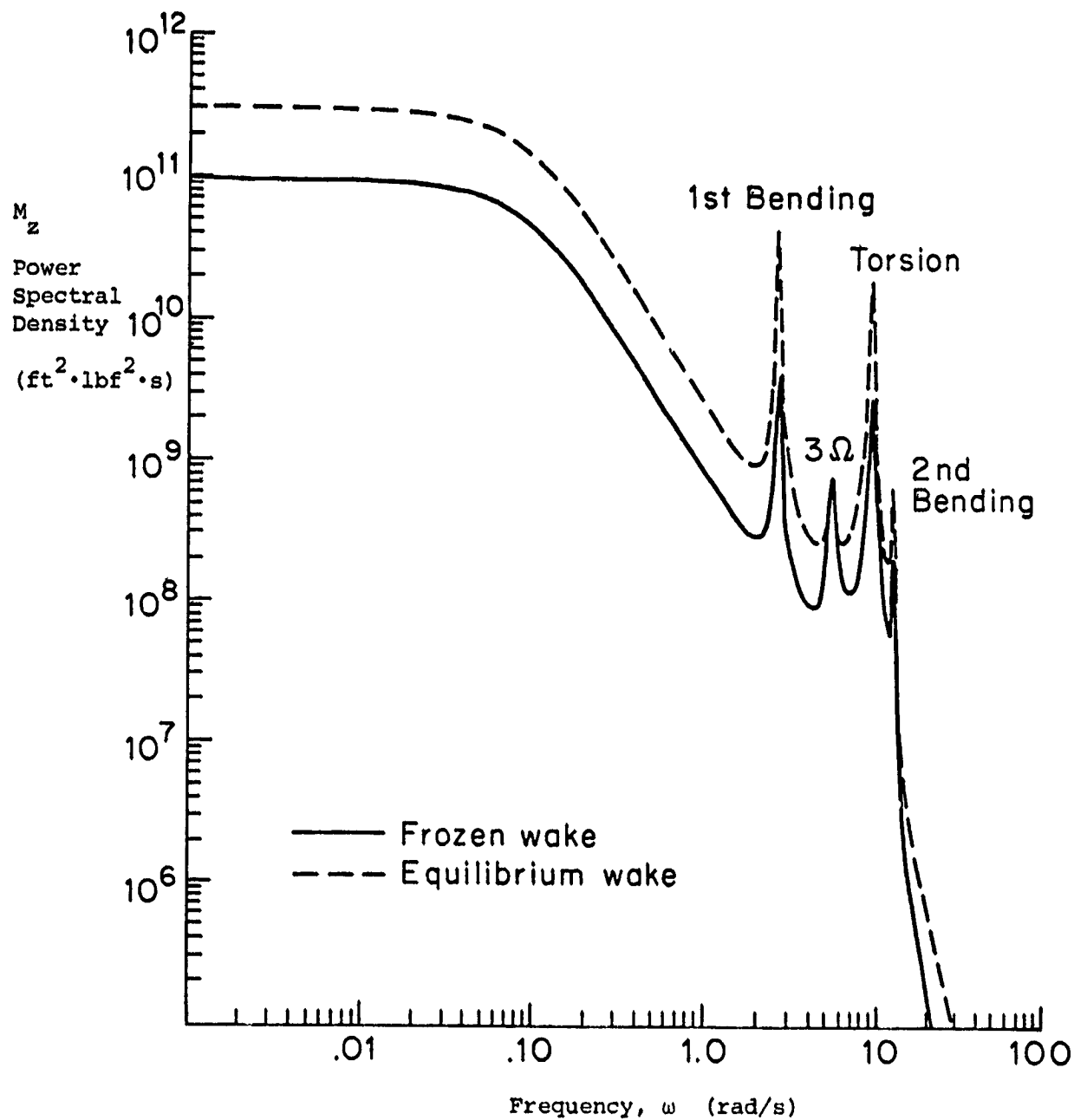


Figure 5. Tower Torsion Load,  $M_z$ , for Mod-G.

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Note that the matrices  $[B]$ ,  $[M]$ , and  $[A]$  depend nonlinearly on the parameters  $V_w$  and  $L$ .

Now, suppose it is desired to compute the probability that  $y$  exceeds a certain critical value  $y_c$ . The conditional probability is given by

$$\Pr\{y > y_c | V_w, \sigma, L\} = \int_{y_c}^{\infty} p(y | V_w, \sigma, L) dy \quad (13)$$

Substituting Eq. (9) into Eq. (13) yields

$$\Pr\{y > y_c | V_w, \sigma, L\} = \frac{1}{2} - \operatorname{erf}\left(\frac{y_c - \mu_y}{\sigma_y}\right) \quad (14)$$

where  $\operatorname{erf}(\cdot) = \frac{1}{\sqrt{2\pi}} \int_0^{(\cdot)} e^{-y^2/2} dy$  = the error function.

The total probability is thus given by

$$\Pr\{y > y_c\} = \int_0^{\infty} \int_0^{\infty} \int_0^{\infty} \left(\frac{1}{2} - \operatorname{erf}\left(\frac{y_c - \mu_y}{\sigma_y}\right)\right) p(V_w, \sigma, L) dV_w d\sigma dL \quad (15)$$

where  $p(V_w, \sigma, L)$  = the joint probability density function of the positive wind and turbulence parameters.

For computational purposes, the integrals can be approximated by discrete summations, so that

$$\Pr\{y > y_c\} = \sum_{j,k,\ell} \left(\frac{1}{2} - \operatorname{erf}\left(\frac{y_c - \mu_y}{\sigma_y}\right)\right) p(V_{wj}, \sigma_k, L_\ell) \quad (16)$$

where the subscripts denote discrete values of the parameters associated with "counting bins." The probability required is the joint probability that  $V_w$  is in bin  $j$ ,  $\sigma$  is in bin  $k$ , and  $L$  is in bin  $\ell$ .

Unfortunately, complete data for determining the joint density function for the wind and turbulence parameters is generally lacking. However, several simplifying assumptions make an approximate model possible.

In an atmospheric boundary layer with neutral buoyant stability the logarithmic profile has been found to adequately model the variation of  $V_w$  with height [9]. This model is of the form

$$V_w = \frac{u_*}{0.4} \ln\left(\frac{z - z_n + z_0}{z_0}\right) \quad (17)$$

where  $u_*$  = friction velocity,  
 $z$  = height above the ground,  
 $z_n$  = nominal height where  $V_w = 0$  (often zero).

$z_0$  = terrain roughness length. OF POOR QUALITY

Frost, et al. [10] recommend the Weibull probability distribution for the steady wind speed at the reference height of 10 m. Thus solving Eq. (17) for  $u_*$  when  $z = z_r = 10$  m yields

$$V_w = V_r \frac{\ln\left(\frac{z - z_n + z_0}{z_0}\right)}{\ln\left(\frac{z_r - z_n + z_0}{z_0}\right)} \quad (18)$$

where  $V_r = V_w$  at the reference height.  
 $z_r$  = reference height.

Since  $V_w$  and  $V_r$  are linearly related,  $V_w$  also satisfies the Weibull distribution which can be differentiated to give the density function of the form

$$p(V_w) = \frac{k}{V_0} \left(\frac{V_w}{V_0}\right)^{k-1} e^{-(V_w/V_0)^k} \quad (19)$$

where  $k$  = a site parameter ( $\approx 2$ ).

$$V_0 = \frac{\bar{V}_w}{\Gamma(1 + \frac{1}{k})}$$

$\bar{V}_w$  = annual mean wind speed at the desired height.  
 $\Gamma(\cdot)$  = gamma function.

The annual mean wind speed at the desired height can be found from the value at the reference height by the use of Eq. (18).

The rms, turbulent component velocity,  $\sigma$ , is found to be highly correlated with the steady wind speed. Panofsky, et al. [11] give the relation

$$\sigma = 2.3 u_* \quad (20)$$

so that when Eq. (17) is used for  $u_*$ ,

$$\sigma = \frac{0.92}{\ln\left(\frac{z - z_n + z_0}{z_0}\right)} V_w \quad (21)$$

The turbulence integral scale,  $L$ , is much less understood. Most evidence indicates that it is independent from the steady wind speed,  $V_w$ , and the variance,  $\sigma^2$ . Several authors [12,13,14] recommend different power laws for the variation of integral scale with height. However, these relations are inconsistent and the experimental data exhibit wide scatter. It is highly recommended that an experimental program be

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undertaken to determine an appropriate height scaling law and to account statistically for the variation observed at a given height. In the interim, we will assume the integral scale is deterministic and satisfies the height relation

$$L = L_r \sqrt{\frac{z}{z_r}} \quad (22)$$

where  $L_r$  = a site parameter ( $\approx 65$  m).  
 $z_r$  = reference height = 10 m.

Using these simplifying approximations for the parameter models, the statistical procedure given by Eq. (15) reduces to

$$\Pr\{y \geq y_c\} = \int_0^{\infty} \left(\frac{1}{2} - \operatorname{erf}\left(\frac{y_c - \mu_y}{\sigma_y}\right)\right) p(V_w) dv_w \quad (23)$$

where  $p(V_w)$  is given by Eq. (19).

The quantities  $\mu_y$  and  $\sigma_y$  will be complicated functions of  $V_w$  given by the model of the turbine response, with Eqs. (21) and (22) used for the parameters  $\sigma$  and  $L$ . Obviously, numerical procedures would be used to perform this computation.

#### ESTIMATION OF MODEL PARAMETERS FROM FIELD DATA

Since the steady wind and turbulence parameters,  $V_w$ ,  $\sigma$ , and  $L$ , critically affect the statistics of the response, it is highly desirable to have a reliable method for extracting the parameters from real field data. One such method is the equation error method [15]. Basically, the method determines a set of parameter values which minimize the difference between the data and predicted values based on the model equations. The resulting parameters will then serve to characterize the turbulence sample observed. A whole collection of such parameter values will then give the required statistical information discussed in the previous section.

Before proceeding to give the detailed procedure for estimating the mean wind and turbulence parameters, a brief description of the equation error method will be given. Suppose we have an accurate, noise-free measurement of a random process,  $u$ , modeled by the stochastic differential equation.

$$\dot{u} = au + bw \quad (24)$$

where  $w$  = white noise with flat PSD =  $S_w$ .  
 $a, b$  = model parameters.

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The measurements will be a set of  $N$  values,  $u(i)$  taken at discrete times with a constant time interval,  $\tau$ , between measurements. The continuous time model can be converted to the discrete time form

$$u(i+1) = e^{a\tau} u(i) + \xi(i) \quad (25)$$

where  $\xi(i)$  = a random sequence of uncorrelated values.

The variance  $\sigma_\xi^2$  of  $\xi(i)$  is found by matching the stationary variance of  $u(i)$  and  $u(t)$ . Thus, from Eq. (25)

$$E[u^2(i+1)] = e^{2a\tau} E[u^2(i)] + E[\xi^2(i)] \quad (26)$$

which when solved yields

$$\sigma_\xi^2 \Delta = E[\xi^2(i)] = (1 - e^{2a\tau}) \sigma_u^2 \quad (27)$$

From Eq. (24) (assuming  $a < 0$ ),

$$2a\sigma_u^2 + b^2 S_w = 0 \quad (28)$$

Using Eq. (28) in Eq. (27) yields

$$\sigma_\xi^2 = (1 - e^{2a\tau}) \left(-\frac{b^2}{2a} S_w\right) \quad (29)$$

Now, since  $u(i+1)$  and  $u(i)$  are linearly related and the noise term is sequentially uncorrelated, standard regression methods [16] can be used to estimate  $e^{a\tau}$  and  $\sigma_\xi^2$  from the data sequence. Thus, we choose the parameter,  $a$ , to minimize the estimated variance

$$\hat{\sigma}_\xi^2 = \frac{1}{N-1} \sum_{i=1}^{N-1} (u(i+1) - e^{a\tau} u(i))^2 \quad (30)$$

The product,  $b^2 S_w$ , is determined from Eq. (29)

$$b^2 S_w = \frac{-2a \hat{\sigma}_\xi^2}{1 - e^{2a\tau}} \quad (31)$$

It is impossible to estimate  $b$  and  $S_w$  separately.

With the mathematical preliminaries out of the way, let us return to the turbulence parameter estimation problem. Suppose we have two

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propeller type anemometers set up to measure orthogonal horizontal components of the wind. Let  $v_1(i)$  and  $v_2(i)$  be sequences of measurements taken from the anemometers. The first step in the procedure is to find the steady wind speed and direction. Thus, determine

$$\langle v_1 \rangle = \frac{1}{N} \sum_{i=1}^N v_1(i) \quad (32)$$

$$\langle v_2 \rangle = \frac{1}{N} \sum_{i=1}^N v_2(i)$$

Now,

$$V_w = \sqrt{\langle v_1 \rangle^2 + \langle v_2 \rangle^2} \quad (33)$$

$$\phi = \tan^{-1} \frac{\langle v_2 \rangle}{\langle v_1 \rangle}$$

The lateral and longitudinal turbulence components are thus determined from

$$v_x(i) = v_2(i) \cos \phi - v_1(i) \sin \phi \quad (34)$$

$$v_y(i) = v_1(i) \cos \phi + v_2(i) \sin \phi - V_w$$

The next step is to determine the parameter,  $L$ , using the equation error regression procedure. According to the model developed by Holley [17], the lateral and longitudinal components of the turbulence satisfy the stochastic differential equations

$$\dot{v}_x = -\frac{2V_w}{L} v_x + \frac{2V_w^2}{L} w_1 \quad (35)$$

$$\dot{v}_y = -\frac{V_w}{L} v_y + \frac{\sqrt{2} V_w^2}{L} w_2$$

where  $w_1$  and  $w_2$  are independent white noise processes with equal power spectral densities,  $S_w = \sigma^2 L / V_w^3$ .

Applying the equation error regression technique of Eq. (30) and normalizing each of the equation errors by the variance gives the variance estimate

$$\hat{\sigma}^2 = \frac{1}{2} \left( \frac{\hat{\sigma}_1^2}{-4V_w \tau / L} + \frac{\hat{\sigma}_2^2}{-2V_w \tau / L} \right) \quad (36)$$

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$$\text{where } \hat{\sigma}_1^2 = \frac{1}{N-1} \sum_{i=1}^{N-1} (V_x(i+1) - e^{-2V_w \tau/L} V_x(i))^2$$

$$\hat{\sigma}_2^2 = \frac{1}{N-1} \sum_{i=1}^{N-1} (V_y(i+1) - e^{-V_w \tau/L} V_y(i))^2$$

The value of  $L$  is chosen to minimize  $\hat{\sigma}^2$  and  $\sigma$  is the resulting  $\hat{\sigma}$  after the minimization.

The parameter values determined by this method will characterize the particular turbulence sample observed during a given sampling period. It is expected that the values will be different for different days and times at which the data is taken. This collection of parameter values can then be used to estimate the statistics discussed in the previous section.

#### CONCLUSIONS

The paper has presented a modeling technique which can be used to estimate wind turbine response statistics due to atmospheric turbulence. Up to this point all of the modeling results have been theoretical. Before these techniques can be put to use by designers, it is required that they be verified using atmospheric and wind turbine field data.

#### ACKNOWLEDGEMENTS

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INHERENT UNCERTAINTIES IN METEOROLOGICAL PARAMETERS  
FOR WIND TURBINE DESIGN

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One of the major difficulties associated with meteorological measurements is the inability to duplicate the experimental conditions from one day to the next. This lack of consistency is compounded by the stochastic nature of many of the meteorological variables of interest. Moreover, simple relationships derived in one location may be significantly altered by topographical or synoptic differences encountered at another. The effect of such factors is a degree of inherent uncertainty if an attempt is made to describe the atmosphere in terms of "universal" laws. In this paper some of these uncertainties and their causes are examined, examples are presented and some implications for wind turbine design are suggested.

The basic design process for a wind turbine typically takes into account a number of wind characteristics. First, some estimates of wind speeds and their frequency of occurrence are needed. This information may be summarized in a probability distribution function of wind speed. However, such information may only be available at a single height, and it then may be necessary to use an extrapolation technique to relate winds at one height to those at another. Finally, the effects of unsteady winds must be taken into account, so some information on turbulence is required as well.

When the basic wind characteristics of interest have been identified, some standard reference work or handbook may be used to quantify these features. Using these values as a design basis, and incorporating some reasonable safety factors where appropriate, the machines may then be built and tested. Mass production and marketing of the turbines follow, based on the expectation that the failure rate will be small, at least in the near future.

This process might work--or it might not. Presumably there are no inherent, fatal design flaws in the current generation of wind turbines and there is a reasonable expectation of success. Nonetheless, it is useful to keep in mind that the wind is temperamental and may often refuse to abide by the laws summarized in standard reference works. It is therefore important that machines not be unduly sensitive to deviations from "expected" wind behavior.

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Let us look at some of these laws and see how and where they were derived. The effects of statistical variability, terrain and thermal influences on these laws can then be considered.

If one is interested in how the wind varies over the course of a year, a probability distribution function is needed. One that is often used is the Weibull distribution,

$$p(V) = \left(\frac{k}{c}\right) \left(\frac{V}{c}\right)^{k-1} \exp \left[ - \left(\frac{V}{c}\right)^k \right] \quad [1]$$

Here,  $c$  is a scale parameter proportional to the mean wind speed and  $k$  is another scale factor that determines the width of the distribution about the mean.

If one wishes to know how this distribution varies with height, a logical starting point is to look at the change in wind speed occurring during a single hour rather than over a whole year. The variation of the wind speed with height depends on a number of factors. If one has a cloudy day, uniform upwind terrain for a distance of a couple of miles or more, and flat terrain, and if one is only interested in the first 30-50 m of the atmosphere above the surface (possibly 100 m if all goes well) then the velocity profile is given by

$$\bar{U}(z) = A \ln \frac{z}{z_0} \quad [2]$$

$\bar{U}$  is the average speed at a height  $z$ ,  $A$  is a constant and  $z_0$  is another constant called the roughness length; it is determined by the nature of the upwind surface. An atmosphere that obeys this relationship is said to behave as a neutral atmosphere.

If preferred, one can pick two heights,  $z_1$  and  $z_2$ , and express the ratio of speeds at these two heights in the form shown below.

$$\frac{\bar{U}(z_2)}{\bar{U}(z_1)} = \left(\frac{z_2}{z_1}\right)^\alpha \quad [3]$$

This is the power law form, and  $\alpha$  is the power law exponent. For  $z_0$  in the range of 1-20 cm (smooth to moderately rough terrain), the log formula predicts that  $\alpha$  will lie in the range 0.12-0.19 for  $z_1 = 20$  m and  $z_2 = 100$  m. Clearly, if the log law is correct, the power law exponent will have to vary as  $z_1$  and  $z_2$  vary.

Finally, the distribution of turbulent energy over various frequencies is given by an expression from Kaimal et al. [1] and Frost et al. [2]

$$\frac{n S(n)}{\sigma_u^2} = \frac{0.164 (n z / 0.0144 \bar{U})}{1 + 0.164 \left( \frac{n z}{0.0144 \bar{U}} \right)^{5/3}} \quad [4]$$

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$S(n)$  is the power spectral density for longitudinal turbulence,  $\sigma_u^2$  is the variance of the fluctuating wind, proportional to the total energy of the fluctuations, and  $n$  is the frequency. The intensity of turbulence is  $\sigma_u/\bar{U}$ . For  $z_0 = 1-20$  cm,  $\sigma_u/\bar{U} \sim 0.11-0.22$  between 20 and 100 m.

The Weibull distribution seems to work more or less well in a variety of situations. The other formulas are for "ideal" cases, but they may not be a faithful representation of conditions that a turbine must live with. There are at least three causes of this--terrain differences, differences in the thermal structure of the atmosphere, and the random nature of the wind. There are often other causes as well, but considerations of these for the remainder of the paper will suffice.

Consider the wind speed distribution at a single height. Justus et al. [3] have done a study of distributions taken from 140 sites in the continental United States. In this study they obtained estimates of the expected statistical spread of Weibull distributions. Some results are shown in Figure 1.

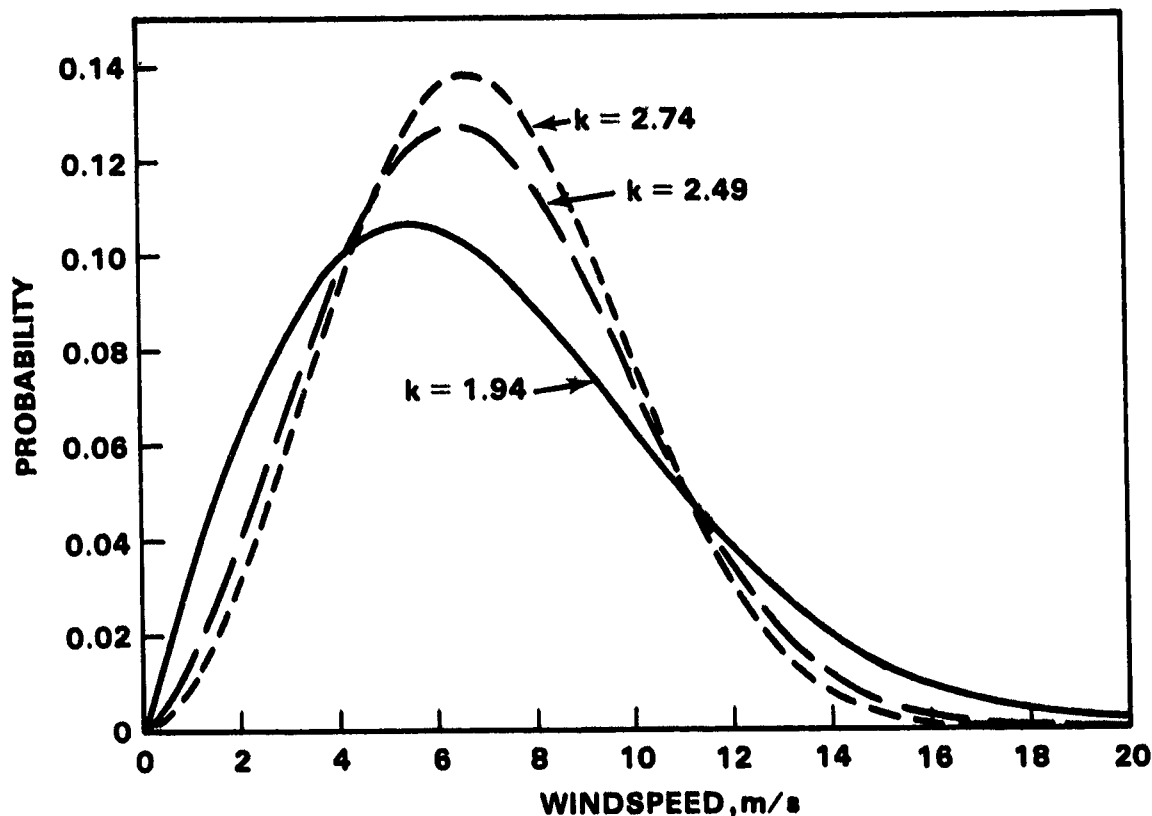


FIGURE 1. WEIBULL WIND SPEED PROBABILITY DISTRIBUTIONS FOR 7 M/S MEAN WIND SPEED AND THREE VALUES OF  $k$

Assume the annual average wind speed is 7 m/s (about 16 mph). Then the mean distribution looks like the curve marked  $k = 2.49$  in the figure.

However, one can expect 10% of the cases to look more peaked than the  $k = 2.74$  curve and 10% to look flatter than the  $k = 1.94$  curve. If one does a simple calculation, one can show that the available power, proportional to  $V^3$ , is 32% higher for the  $k = 1.94$  curve than for the  $k = 2.74$  curve. The actual difference in extracted power, of course, might be less.

Thus far the assumption has been that the mean wind speed is actually 7 m/s. However, Corotis [4] has shown that if measurements are taken for a year to attain an annual average speed, there is a 30% chance that next year's annual average speed will differ from this year's by 10% or more. This is an inescapable result of the stochastic nature of the wind.

Now assume one has the wind speed distribution at one height and wishes to extrapolate it to another height. Justus and Mikhail [5] have also proposed a set of formulas that will do this. Figure 2 shows how well one of them works.

Here the ratio of extrapolated to measured  $c$  values, at some upper level, is plotted on the  $y$  axis as a function of the  $c$  values at the lower level, plotted on the  $x$  axis. Recall that  $c$  is essentially a measure of the mean wind speed. This plot then gives an estimate of how well one can extrapolate the mean wind speed from one level to another on an annual basis. A value of one for the ratio would be perfect. One can see that the formula works well in the mean, but there is a considerable amount of scatter. The data were taken from measurements at nuclear power plant sites, and wind turbines might well be located in terrain with far more complexity. In such cases the scatter could be worse. The implications for estimates of potential energy capture are serious. If  $c$  is overestimated, the energy will be, too; from the figure, errors of 20% are seen to be quite common.

Thus far, only statistical variations have been considered. What happens when other factors such as terrain or the thermal structure of the atmosphere are explicitly taken into account? Under "ideal" conditions one gets a neutral atmosphere and the wind speed increases with the logarithm of the height. A condition for this is that the terrain upwind of the measuring point be uniform and flat. Under many circumstances, however, the turbine site is unlikely to be particularly level or uncluttered. It should not come as a surprise, then, if the wind characteristics at turbine sites differ widely from those at "ideal" sites.

Consider a plot of the distribution of power law exponents that are obtained at a flat site. Recall that the power law exponent depends on the heights at which the wind speeds are measured. It also depends on the roughness length and the thermal structure of the atmosphere. Figure 3 shows some results obtained at Meade, Kansas for moderately strong wind cases, i.e., 8 m/s or larger at a height of about 10 m. There is a peak at a value of  $\alpha$  a little larger than 0.1, about what one might expect from the previous discussion.

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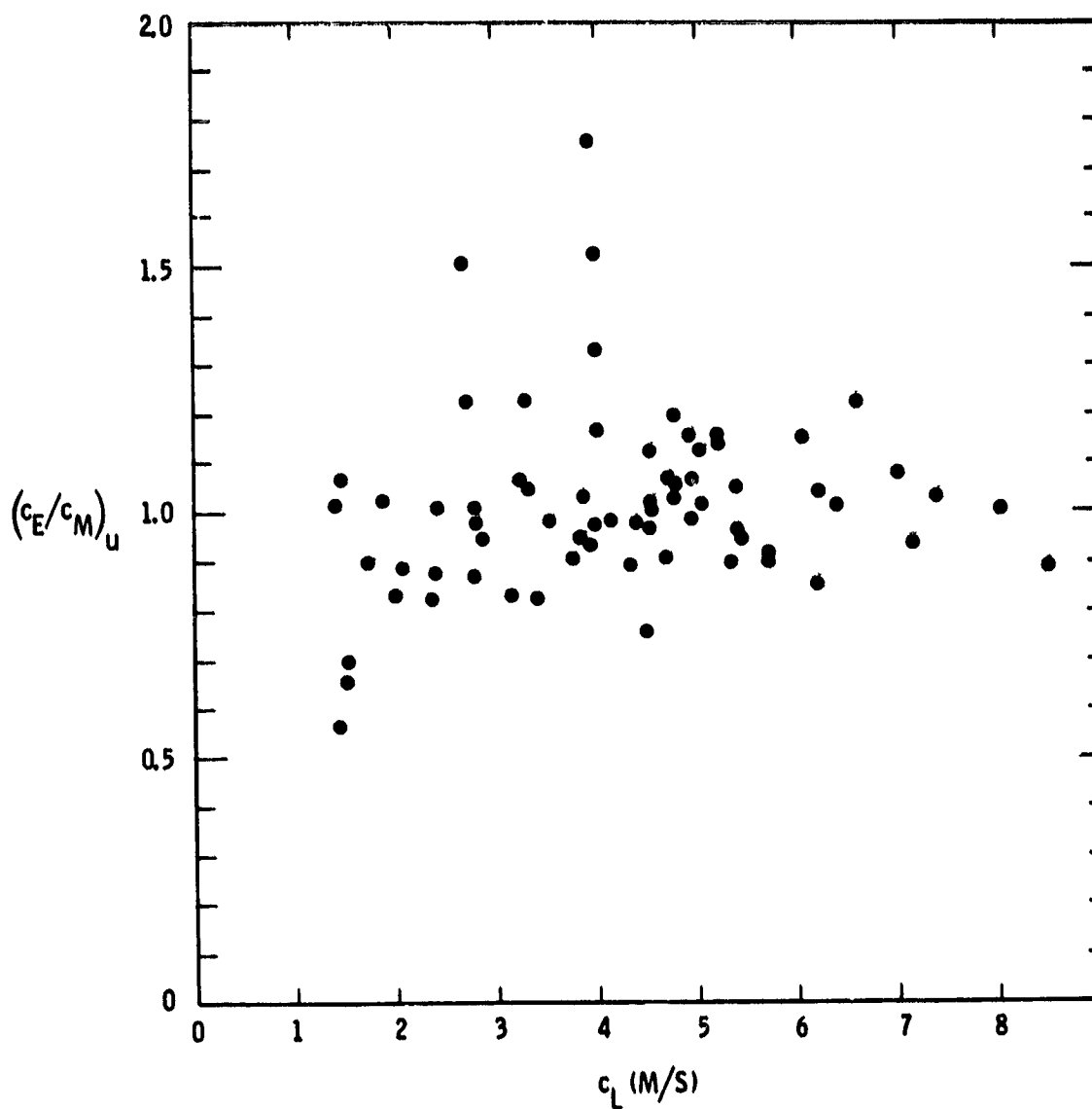


FIGURE 2. RATIOS OF EXTRAPOLATED TO MEASURED VALUES OF  $c$  AT UPPER LEVELS VERSUS MEASURED VALUES OF  $c$  AT LOWER LEVELS

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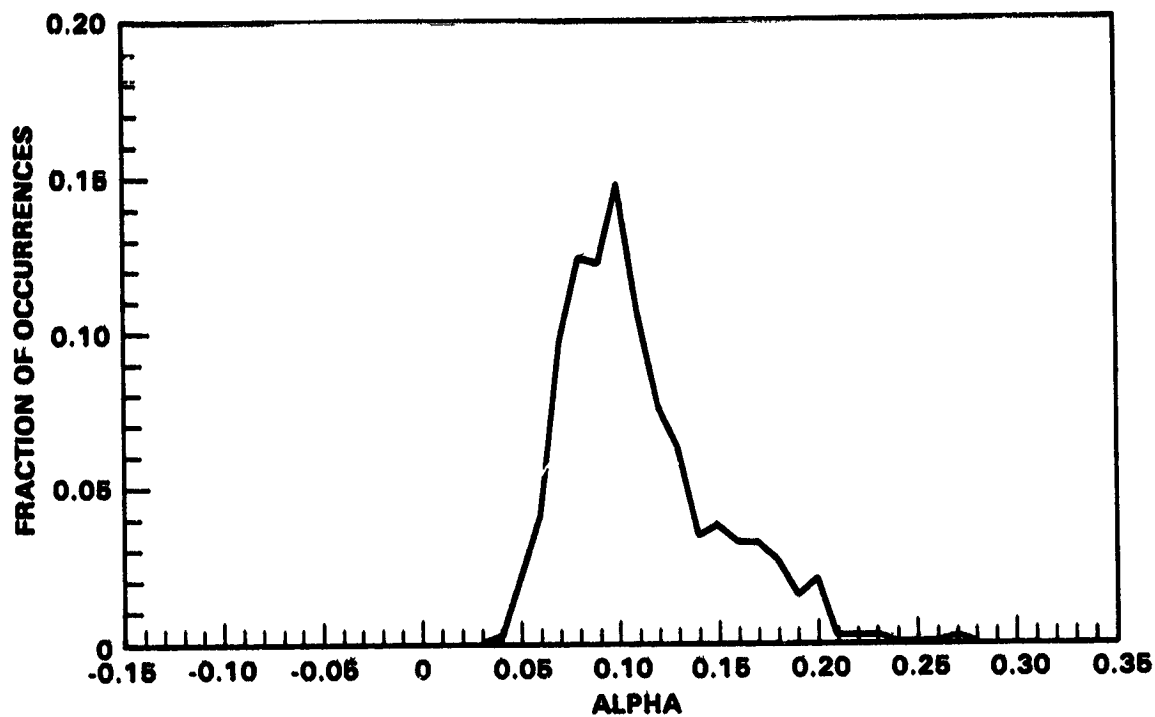


FIGURE 3. WIND SHEAR EXPONENT FREQUENCY DISTRIBUTION NEAR MEADE, KANSAS

Now consider results from a second site, Wells, Nevada.

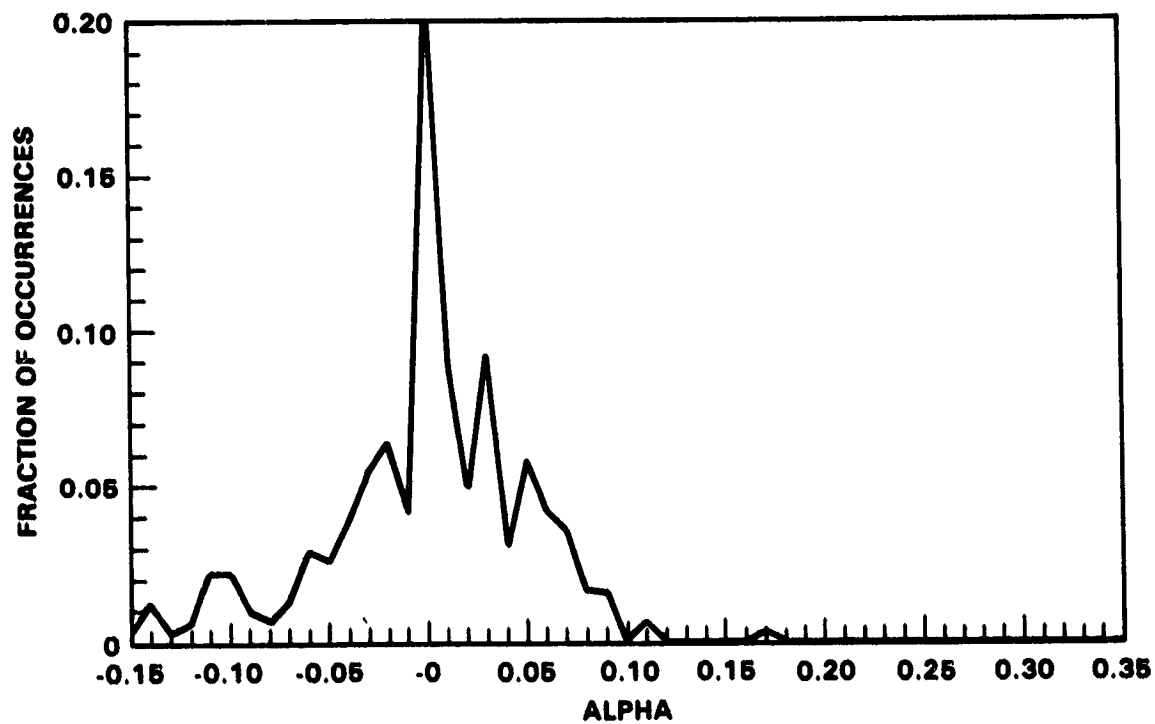


FIGURE 4. WIND SHEAR EXPONENT FREQUENCY DISTRIBUTION NEAR WELLS, NEVADA

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One can see that the power law distribution is quite different. The peak is now at a value near zero and there are a large number of cases where the wind speed hardly changes at all with height or actually decreases. What has gone wrong here? A glance at a topographical map provides one possible explanation.

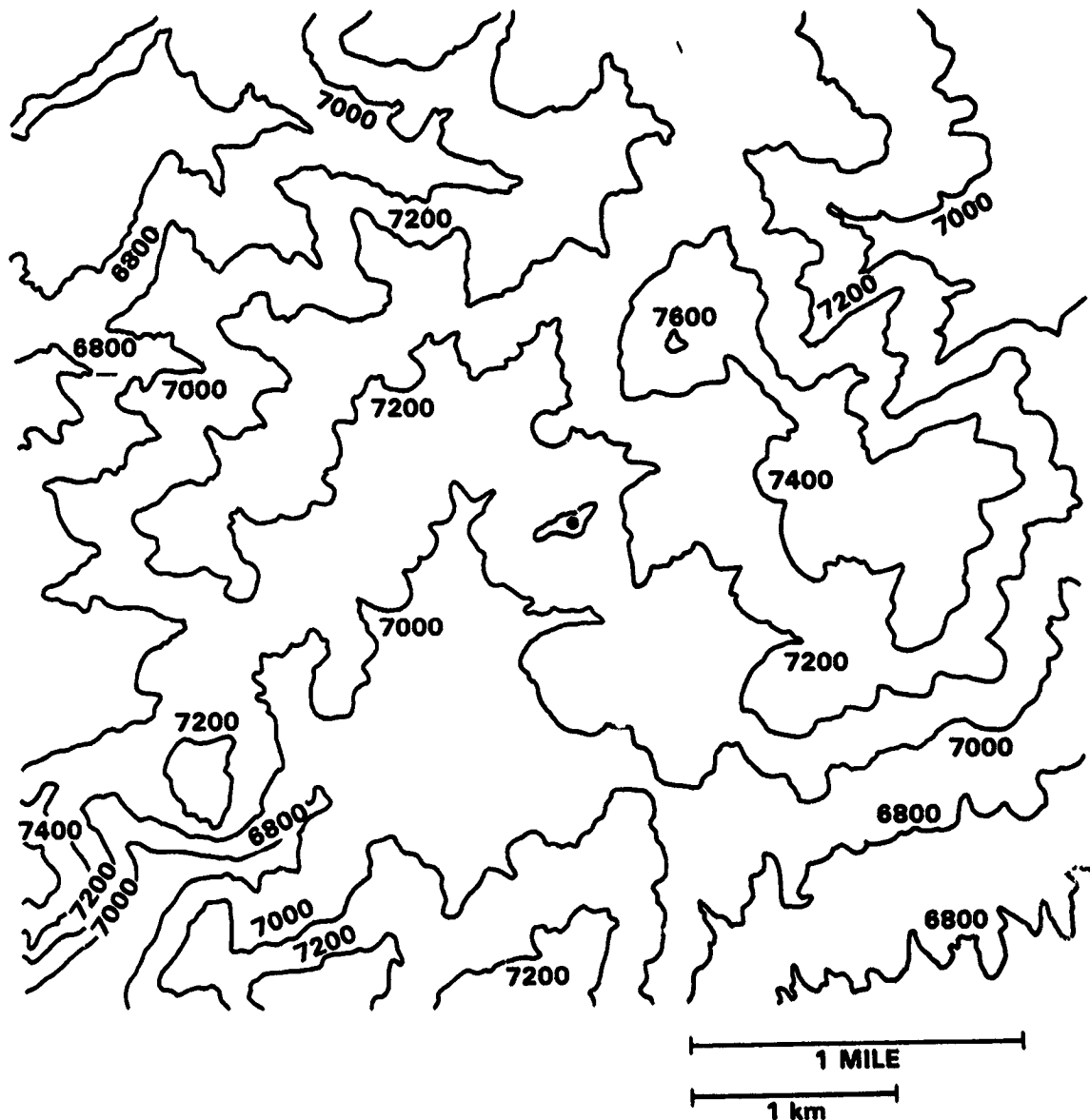


FIGURE 5. TOPOGRAPHICAL MAP OF AREA NEAR WELLS, NEVADA;  
● INDICATES POSITION OF SHEAR MEASUREMENTS

The terrain is relatively complicated, and there is no reason to suppose that the wind behavior at this site will be the same as that at a much flatter one.



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Another important factor for wind profiles is the thermal stability of the atmosphere. Figure 6 shows some profiles obtained by Tielemann [6] at Wallops Island on the Atlantic coast. They were taken for directions such that the wind first traveled over the ocean and then over a short stretch of beach before hitting the tower used for the measurements. As one might expect, for these moderately strong winds the speed increases with the logarithm of the height. However, the nature of the upwind terrain would also lead one to expect a roughness length of 10 cm or less. Instead, the two plots on the left give values between 1 and 4 m, leading to much larger shears than anticipated. For the curve on the left, the power law exponent up to 60 m is  $\lambda \approx 0.5$ .

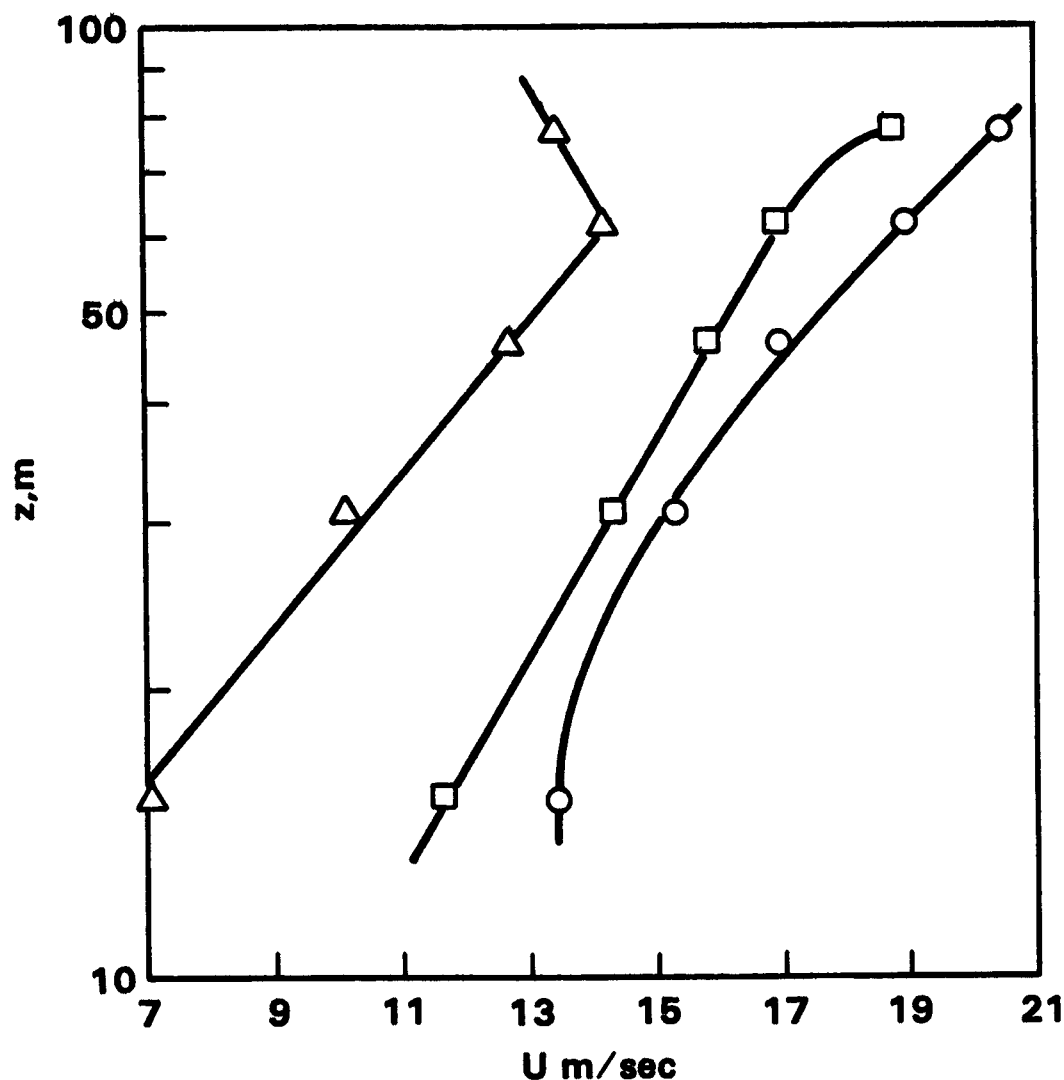


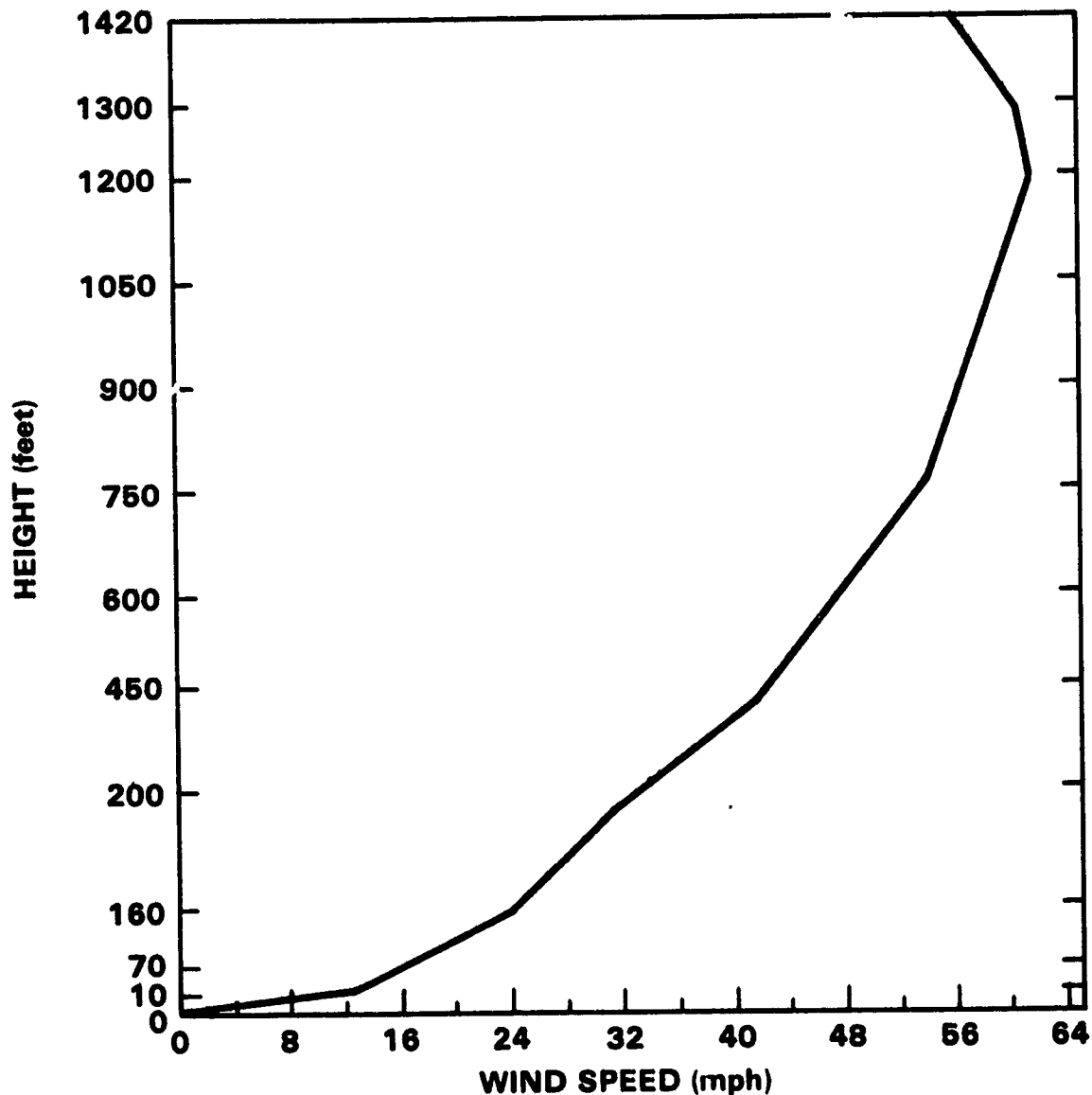
FIGURE 6. WIND PROFILES MEASURED AT WALLOPS ISLAND, VIRGINIA

What has happened is that the thermal effects on the atmosphere due to the proximity of the ocean have altered the structure of the wind. One no longer has a situation in which the turbulence is controlled solely

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by mechanical processes, and all those simple laws discussed earlier don't really apply. There is a comforting myth that if one has strong wind speeds the atmosphere can be treated as neutral; here are several examples that show this is indeed a myth. Tielemann suggests that this situation is quite common--strong winds, good energy potential but no simple wind profile.

A second example of the effects of stability is obtained by considering the phenomenon of nocturnal wind shears. These arise when strong surface cooling effectively decouples the winds at higher elevations from the frictional influence of the ground. A particularly severe case is the one shown in Figure 7, taken from data obtained from a tower in Oklahoma.



**FIGURE 7. EXAMPLE OF NOCTURNAL SHEAR**

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Once again the power law exponent approaches a value of 0.5; if a turbine is sensitive to large shears in the vertical, this could lead to some potentially serious problems.

So far the discussion has been limited to mean shears, i.e., shears of winds averaged for some period ranging between about 10 min and 1 hr. It is clear that the height extrapolations can be a tricky business. These difficulties can lead to poor estimates of energy capture or more severe shears than are desirable. There is another aspect of shears that is often overlooked but that could also produce stress on a blade higher than anticipated. That aspect is the fluctuating behavior of wind shear, and these can routinely produce some surprisingly high shear values even in areas where the mean shear appears relatively benign.

Figure 8 shows the distribution of shears measured over relatively smooth terrain in eastern Washington. The abscissa gives the difference in wind speed between two levels separated by 34.5 m ( $\sim 113$  ft), and with a mean height of 36.6 m. The speed at the lower level was 12 m/s (27 mph) and the test lasted 2 hr. A  $1/7$  power law, a frequently used approximation for strong winds, corresponds to a velocity difference of 1.9 m/s. It is clear that much larger velocity differences are quite common.

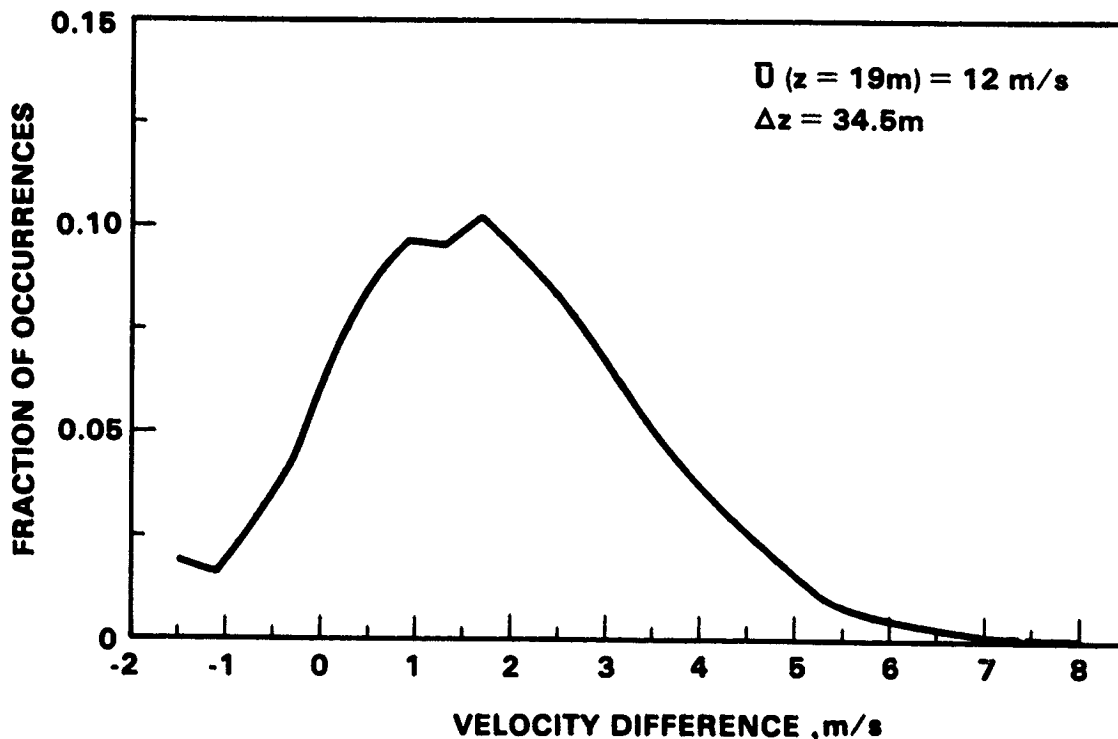


FIGURE 8. DISTRIBUTION OF WIND SHEARS MEASURED  
NEAR RICHLAND, WASHINGTON

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Figure 9 shows the probability of the shear being less than or equal to a given amount, for a more general case. The shear here is expressed in normalized form;  $\Delta u$  is the fluctuating shear,  $\Delta \bar{u}$  is the mean shear and  $\sigma_{\Delta u}$  is the standard deviation of the fluctuating shear. This last quantity is roughly equal to the mean shear, so the ordinate is roughly a measure of the number of multiples of the mean shear by which the mean shear is exceeded. Values of shear three or more times the mean are readily obtained. This is a factor to be considered carefully when estimating the stresses a turbine blade might experience.

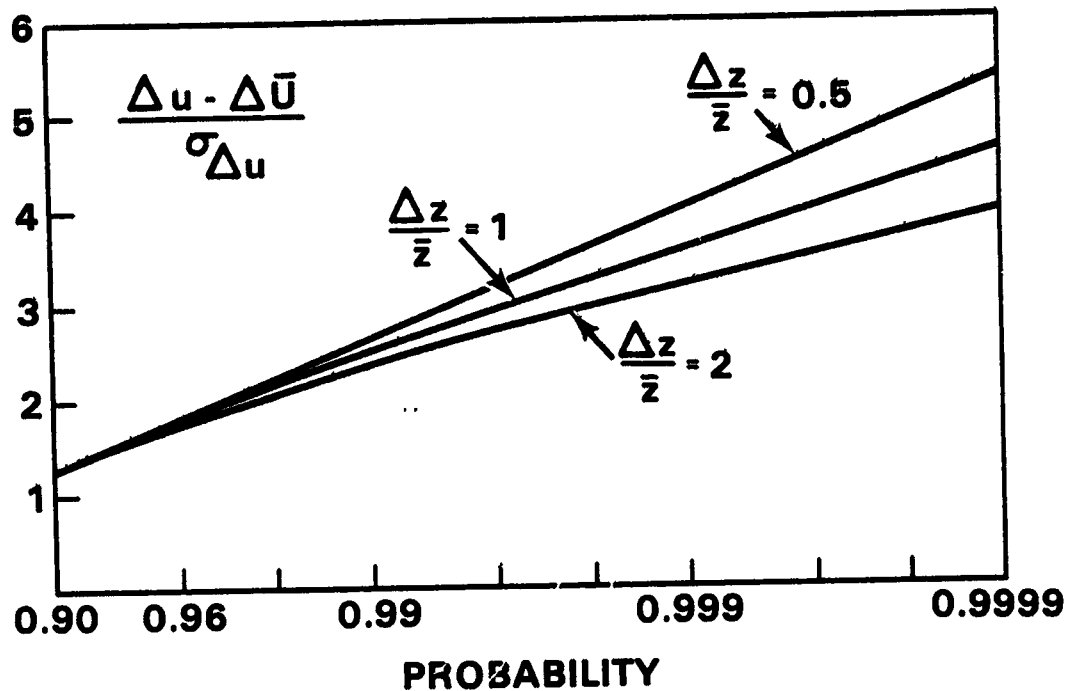


FIGURE 9. PROBABILITY OF NORMALIZED WIND SHEAR BEING LESS THAN A GIVEN VALUE

Now consider another aspect of wind fluctuations, viz., turbulence spectra and turbulent intensity. The spectrum tells how the turbulent energy is divided into various frequency domains. A design spectrum might be of the form suggested by Kaimal et al. [1] and Frost et al. [2] and given in Equation (3). Its form looks like that shown in Figure 10.

However, this form only applies under very slightly stable atmospheric conditions, and it is quite possible to get brisk winds under other conditions as well.

Figure 11 shows a plot made by Powell using a theory of Kaimal [7], which shows how the spectrum is modified under very slightly unstable conditions. The  $z_i$  is the height of the lowest inversion in the atmosphere. There is quite a bit more energy in the low frequency end of the spectrum.

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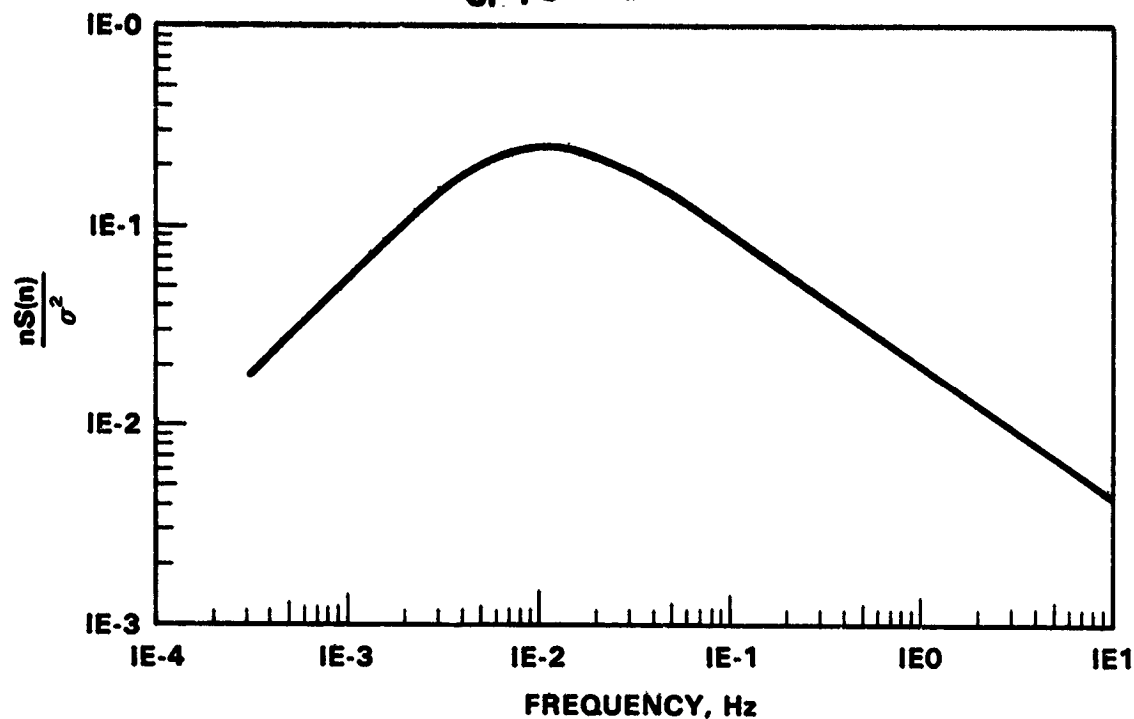


FIGURE 10. NORMALIZED SPECTRUM OF LONGITUDINAL TURBULENCE FOR NEUTRAL LIMIT OF STABLE CONDITIONS,  $\bar{U} = 10$  M/S,  $z = 50$  M

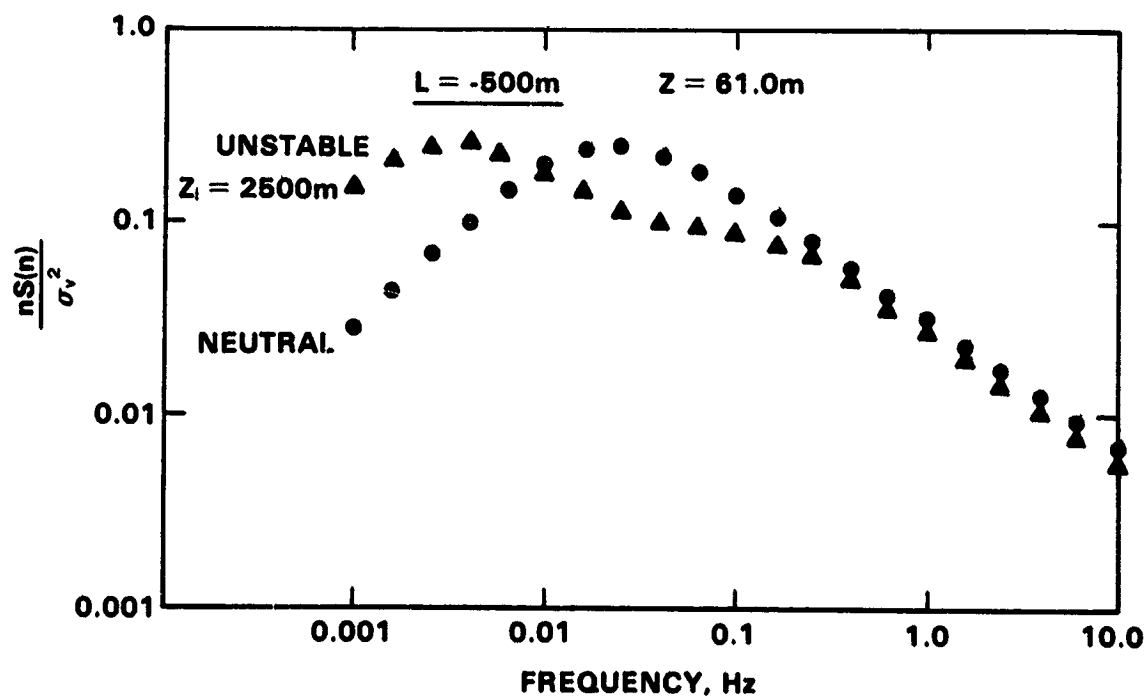


FIGURE 11. COMPARISON OF NEUTRAL SPECTRUM WITH UNSTABLE SPECTRUM,  $\bar{U} = 13.3$  M/S

All of this discussion again assumes that the terrain surrounding the measuring point is quite simple. In fact, the theory for the unstable spectrum shown here was developed, in part, using data taken from a site that had about a 20 m elevation difference in a distance of 16 km. It should not come as a surprise, then, if rougher terrain affects the form of the spectrum. Dutton and his co-workers [8] reported on some spectra measured in a hilly region of Pennsylvania. Some results are shown in Figure 12.

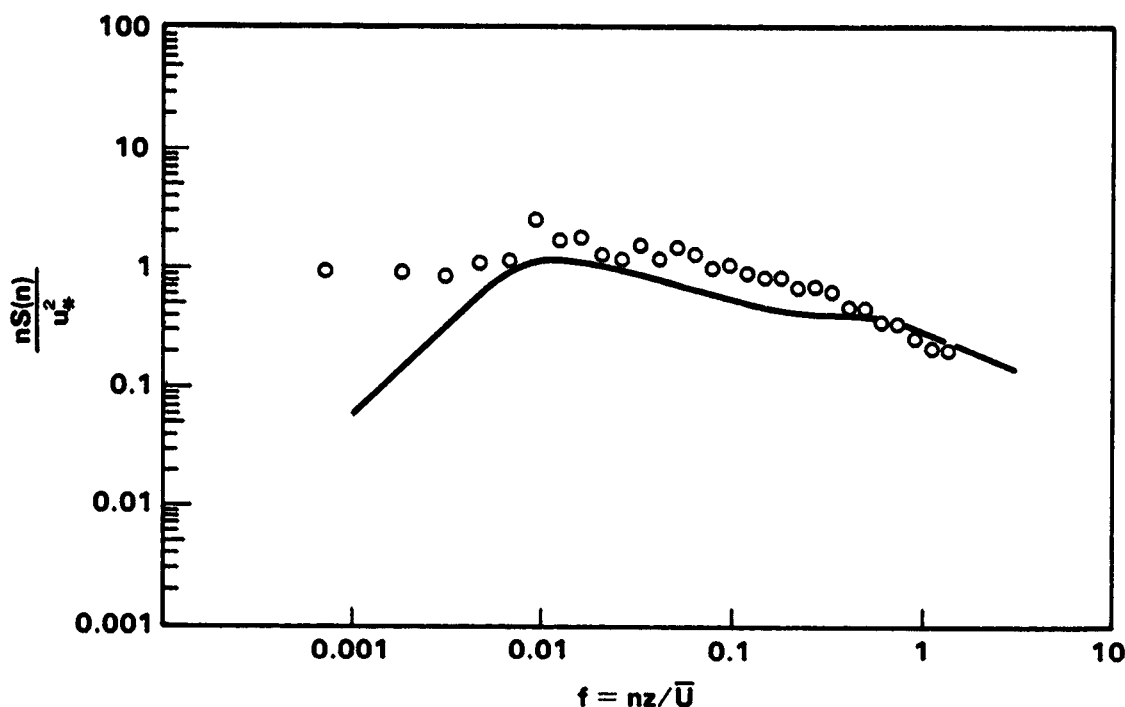


FIGURE 12. COMPARISON OF UNSTABLE SPECTRUM OVER FLAT TERRAIN (LINE) WITH UNSTABLE SPECTRUM IN HILLY TERRAIN (POINTS)

Here the solid line is an unstable spectrum applicable to the flat terrain case; the symbols are experimental results and show an even larger increase in the low frequency portion of the spectrum. This portion may well be relevant to yawing or control strategies and perhaps even to structural fatigue.

One often summarizes the behavior of the spectra--at the risk of losing some information--by merely specifying the turbulent intensity. This is equivalent to integrating under the whole spectrum to get the turbulent energy, taking the square root of that and then dividing by the mean speed. What are typical values of this quantity? It all depends on when and where one does the measurement. Powell has reviewed some data, taken over flat terrain, on the variation of turbulent intensity with stability.

In Figure 13, the ordinate is the turbulent intensity and the abscissa is the Richardson number, a measure of the stability. All these data

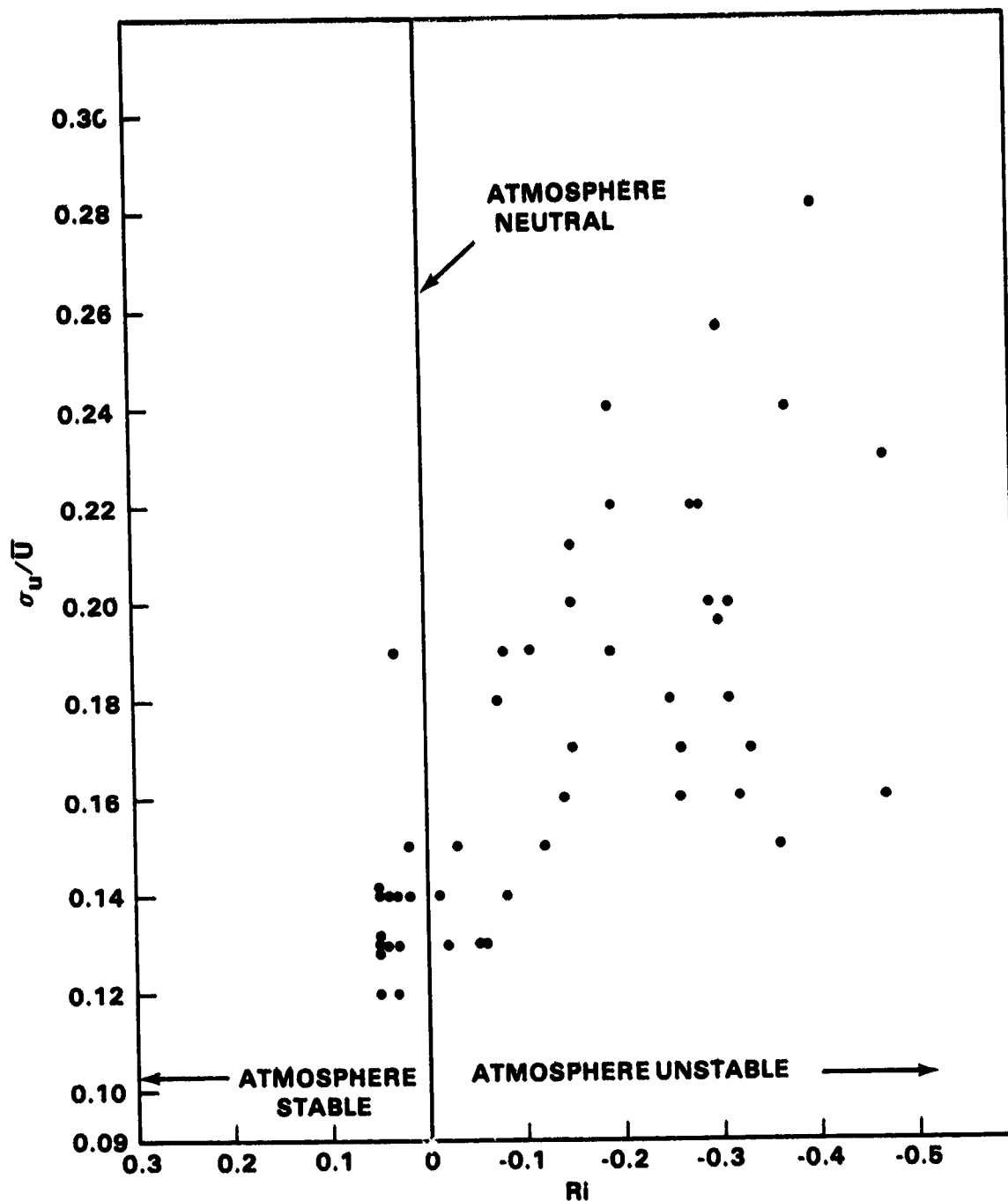


FIGURE 13. VARIATION OF TURBULENCE INTENSITY WITH STABILITY DURING MODERATELY STRONG WIND CONDITIONS

were taken during relatively windy conditions, well within the operating range of most turbines. The range of values is enormous. Much of it is attributable to increased low frequency contributions in the turbulent spectrum. Some scatter, however, is not well described by current theories.

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The influence of terrain may also be seen by examining some of the figures given in Table 1.

TABLE 1. TURBULENT INTENSITY  $\sigma_u/\bar{U}$

Site	Type	z	$\bar{U}$	$\sigma_u/\bar{U}$
Hanford, WA	Flat	37 m	12-18 m/s	0.125
Boone, NC	Hilltop	69 m	11-18 m/s	0.143
White Sands, NM	Escarpment Edge	16 m	10-13 m/s	0.464

The data here represent only a few sets of measurements, but there is a striking difference between the first two sites and the last. Winds blowing up over the edge of the escarpment result in severe turbulence 16 m (about 50 ft) above the ground. It is certainly not the turbulence level one would get from an examination of data taken at the Bonneville Salt Flats.

In summary, what can be concluded from all this? Are handbook descriptions of the wind useless? Not at all. However, one must remember that their values should not be regarded in the same way as the specification of the tensile strength of some material or the electrical resistance of a given diameter wire. In many cases they may just be a description of some atmospheric properties found in simple terrain under ideal conditions. They are quite useful as a starting point in design, but if the performance or integrity of a machine depend critically on any of these atmospheric descriptors, extreme caution is advised.

The title of this paper contains the words "inherent uncertainties". In a sense this is a bit unfair. We are now in a position where many of the effects of atmospheric stability and terrain on various meteorological variables are understood. It is also possible to assess other situations where such effects might be important, even if one can't always make a quantitative prediction of their magnitude. Thus, at least some of the uncertainty really arises from attempts to pigeonhole the behavior of the atmosphere without explicitly allowing for effects we know are important. If one does this, he must expect wide variations about the mean quantities.

There is still a degree of scatter that is not fully understood, however, or that arises from the random character of the atmosphere. Whatever the reason for the so-called "uncertainties", the design process must clearly allow for a degree of flexibility, for too rigid an adherence to allegedly standard atmospheric characteristics could well prove troublesome in the long run.



#### ACKNOWLEDGMENT

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POTENTIAL ERRORS IN USING ONE ANEMOMETER  
TO CHARACTERIZE THE WIND POWER OVER AN ENTIRE ROTOR DISK

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## INTRODUCTION

There has not been much consensus in the wind energy industry on wind measurement strategies used to site large wind turbines. Since energy production estimates based on the wind measurements directly affect the expected cost of energy (and therefore the viability of a site), it is critical that appropriate wind measurements be taken.

A key issue of concern has been what height(s) above ground the wind should be measured. Essentially, there are three strategies:

1. measure continuously at one height on a short tower, typically 10 m. This is relatively inexpensive, but requires one to assume a vertical profile to estimate winds in the approximately 15 to 100 m layer in which a large turbine operates.
2. measure continuously at 10 m and intermittently at higher levels (e.g., kites) to estimate the wind shear with height.
3. measure continuously at three or more levels on a tall (roughly 60-150 m) tower, suitably representative of the entire rotor disk. This is by far the most expensive, but one can determine actual effective rotor disk winds.

Wind data collected at four levels on a 90-m tower in a prospective wind farm area are used to evaluate how well the 10-m wind speed data with and without intermittent vertical profile measurements (strategies 2 and 1, respectively) compare with the 90-m tower data. If a standard, or even predictable, wind speed profile existed, there would be no need for a large, expensive tower. This cost differential becomes even more significant if several towers are needed to study a prospective wind farm.

When only 10-m data are available, wind speeds are typically extrapolated with a vertical profile power law to determine the corresponding hub height wind:

$$V_z = V_{10} \left( \frac{z}{10} \right)^\alpha$$

where

$V_z$  = wind speed at hub height

$V_{10}$  = wind speed at 10 m

$z$  = hub height (m)

$\alpha$  = power law exponent

This extrapolated speed is then used to estimate power output of a turbine. One major problem with this approach is how to specify the power law exponent  $\alpha$ . A value of 1/7 is often used because literature cites it as a typical or average value.

However, this is a great oversimplification and may be totally inappropriate. The vertical profile of wind speed is a complex function of surface roughness (Munn, 1973), stability/time of day (Mahrt and Heald, 1979), and topographic orientation (Hiester and Pennell, 1981).

Over flat terrain the 1/7 power law may be reasonable. But most sites for wind energy development will be on hills, ridges, or in passes; i.e., terrain features likely to accelerate or retard flow in the surface boundary layer. Data from Pacific Gas and Electric Company's (PGandE) 90-m tower demonstrate that alpha over such terrain can be substantially less than 1/7.

## STUDY PROCEDURES

Three items are discussed in this section:

- . PGandE wind energy measurement program.
- . The data base used for evaluating monitoring strategies.
- . Processing of the data.

### PGandE Wind Energy Measurement Program

PGandE has been investigating wind energy potential in the Solano County area near San Francisco, California for the past few years. This area is a low gap in the central California coastal range through which cool marine air streams eastward into the interior valley during the warm season (Figure 1).

There are currently eight monitoring sites in Solano County--five 10-m towers, two 30-m towers, and one 90-m tower. The 90-m tower, called S-01, is located on a flat spur ridge east (downwind in summer) of the main ridgeline of the area (Figure 2).

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The 90-m tower was installed in June, 1980. There are four monitoring levels--10, 30, 60, and 90 m. Wind speed and direction are measured by a Teledyne Geotech Model WS201 Wind Systems. One-half second averaged samples are recorded every two seconds. These data were recorded only on strip charts until mid-September, 1980. After this date, processed data were recorded on cassette tapes in addition to the strip charts.

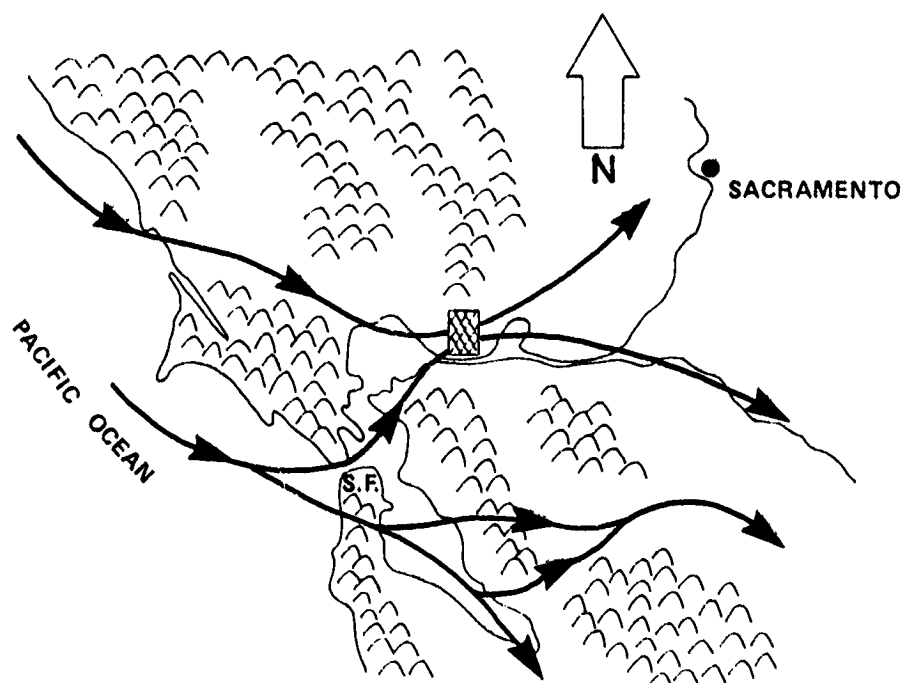


FIGURE 1. TYPICAL SUMMER AIRFLOW PATTERNS IN THE SAN FRANCISCO BAY AREA. SOLANO AREA MARKED WITH CROSS-HATCHING.

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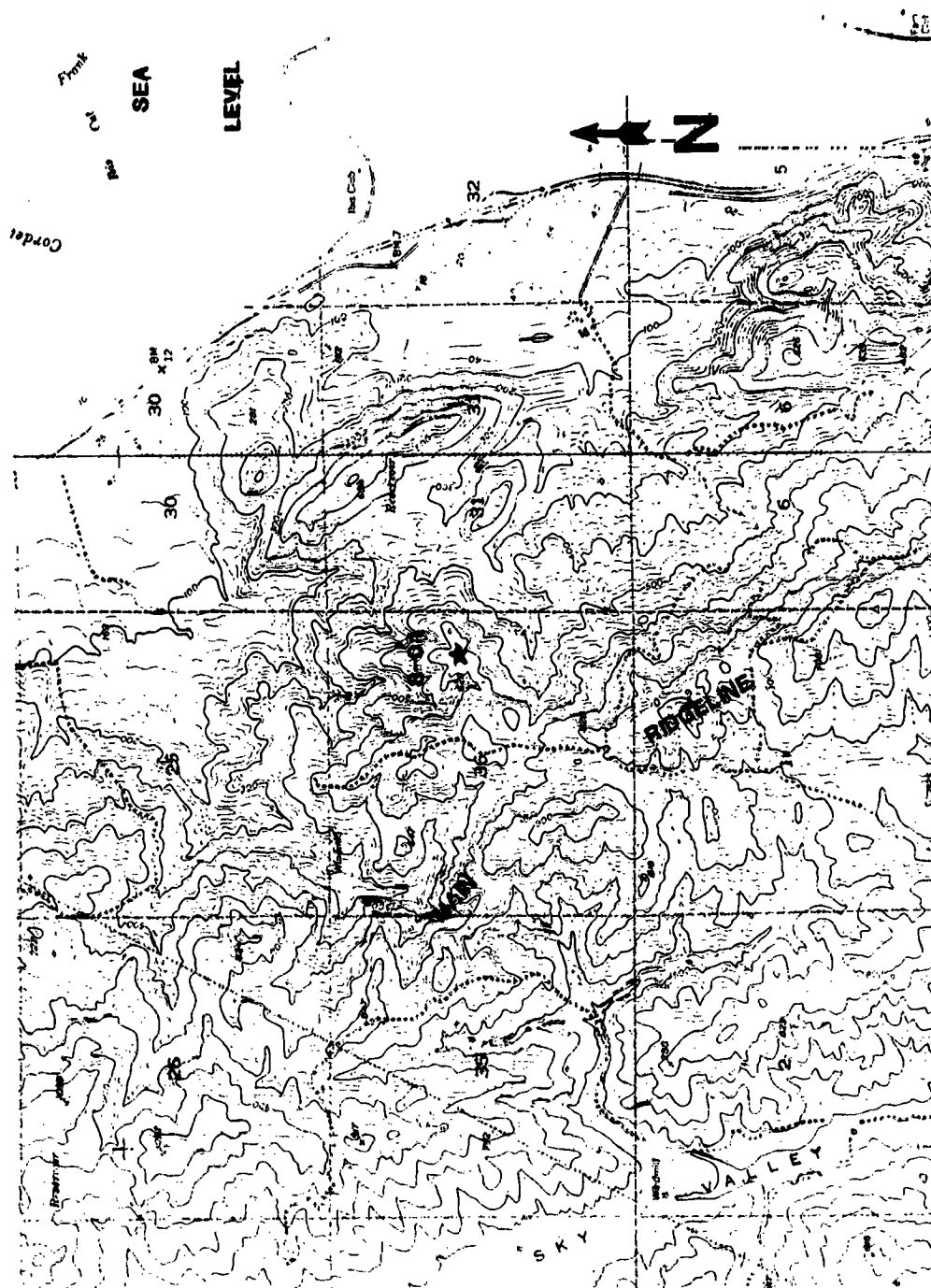


FIGURE 2. S-01 SITE MAP. ELEVATIONS IN FEET.  
1 inch = 1 km.

### Data Base Used for Evaluation of Monitoring Strategies

Since summer is the peak wind season, it was selected to be the data base for this study. The exact dates are June 14, 1980, to September 30, 1980.

Only hours with valid wind speeds at all four levels of a tower were used. There were 2163 hours meeting this requirement, 83 percent of a possible 2616 hours.

One direct and five indirect techniques for estimating the effective rotor disk wind speed were chosen, and a data set with these six estimates for all valid hours was generated for further analysis. Since PGandE had purchased a BWT 2560 (MOD-2), its performance curve was chosen for use in this study. The six techniques were:

1. Effective rotor disk wind speed. This is the direct technique. It is a cubic-weighted mean incorporating all four wind speeds and wind directions. It assumes that all parts of the rotor disk contribute equally to the energy production, subject only to variations in wind speed across the disk (Jim Connell, PNL, personal communication). The formula for a BWT 2560 is:

$$\begin{aligned} \text{VRD} = & \{ [0.11(V'_{300} + 0.25(V'_{300} - V_{200}))^3] + \\ & [0.049(V'_{300} + V_{200})^3] + [0.049(V_{200} + V'_{100})^3] + \\ & [0.11(V'_{100} + 0.35(V'_{30} - V'_{100}))^3] \}^{1/3} \end{aligned}$$

where VRD = the effective rotor disk wind speed,  $V'$  = the wind speed at a given level multiplied by the cosine of the angle between the wind direction at that level and the wind direction at 60-m. (This accounts for direction shears.)

2. Wind speed at 10 m. This technique assumes no change of wind speed with height ( $\alpha = 0$ ).
3. Wind speed at 60 m (hub height of a BWT 2560).
4. Wind speed at 10 m extrapolated to hub height with a  $1/7$  power law. This is the conventional method used in most site evaluations.
5. Wind speed at 10 m extrapolated to hub height with an alpha derived from 5 random days of 90-m tower data, using only hours between 0500 and 2000 PST when the 10-m wind speed exceeded 4 mps.

This exponent  $\alpha$  was computed slightly differently. The usual method is to use the 10-m and 60-m wind speeds to get the power law exponent between those levels. However, we replaced the 60-m wind speed with VRD, since VRD is the direct estimate of the rotor disk wind speed. Based on this method, the effective exponent at S-01 was 0.06.

6. Wind speed at 10 m extrapolated to hub height with an exponent derived from a randomly-selected four-day period of 90-m tower data. This technique is identical to (5) except for the dates. At S-01, the exponent was 0.04.

For sake of brevity, abbreviations for these different techniques will be used as follows:

VRD--effective rotor disk wind speed

V10--10-m wind speed (no extrapolation)

V60--60-m wind speed

HUBXP--10-m wind speed extrapolated with  $\alpha = 1/7$

HUBK1--10-m wind speed extrapolated with  $\alpha$  determined from five random days of tower data.

HUBK2--10-m wind speed extrapolated with  $\alpha$  determined from four consecutive days of tower data.

#### Processing of the Data

The following were computed for the entire study period:

- . Wind rose (VRD only), using 60-m wind direction
- . Mean diurnal speeds (all techniques) and mean diurnal  $\alpha$  (10-VRD)
- . Mean available power (all techniques)
- . Frequency distributions of  $\alpha$  (10-VRD and 60-90)
- . Frequency distributions of wind speed (all techniques)
- . BWT 2560 power output simulations (all techniques)

A comparison of summer and winter mean profiles was also made. Results are discussed in the next section.

\*The 95 percent confidence limits for estimating the mean summer  $\alpha$  computed this way (five random days) were about  $\pm 0.02$  from the actual mean.

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## RESULTS

### Wind Rose

The wind rose for S-01 is shown in Figure 3. Summer winds are from the southwest through west with only minor exceptions.

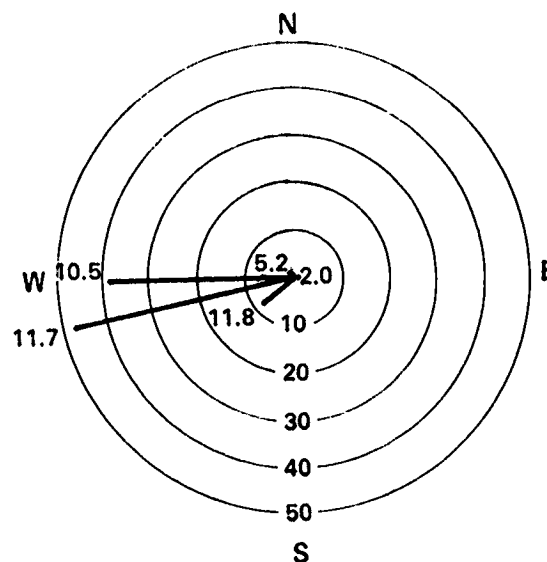


FIGURE 3. S-01 WIND ROSE, SUMMER 1980. AVERAGE WIND SPEED (mps) GIVEN FOR EACH DIRECTION, PERCENTAGE FREQUENCY OF EACH DIRECTION INDICATED BY CIRCLES.

### Mean Diurnal Speeds

Mean diurnal and overall wind speeds are shown for S-01 in Table 1.

Clearly this site does not exhibit a standard vertical profile. There is a reverse in the mean wind shear, with highest winds occurring at 60 m.



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TABLE 1. MEAN DIURNAL WIND  
SPEEDS (mps) AT S-01, JUNE 14, 1980 - SEPTEMBER 30, 1980

Hour (PST)	Number of Obser- vations	<u>Speed</u>							
		<u>V30</u>	<u>V100</u>	<u>V200</u>	<u>V300</u>	<u>VRD</u>	<u>HUBXP</u>	<u>HUBK1</u>	<u>HUBK2</u>
01	90	11.3	12.4	12.7	11.6	12.2	14.8	12.6	12.2
02	90	11.1	12.3	12.4	11.4	12.0	14.6	12.5	12.0
03	89	10.9	12.0	12.2	11.3	11.8	14.3	12.2	11.7
04	87	10.5	11.7	11.8	10.9	11.5	13.8	11.8	11.3
05	86	10.3	11.4	11.3	10.3	10.9	13.5	11.5	11.1
06	85	9.8	10.8	10.7	9.7	10.4	12.9	11.0	10.6
07	83	9.4	10.3	10.0	9.1	9.7	12.4	10.6	10.2
08	86	8.7	9.5	9.3	8.5	9.1	11.4	9.7	9.4
09	86	8.3	9.1	9.3	8.2	8.9	10.9	9.3	9.0
10	92	8.0	8.8	9.1	7.8	8.6	10.5	9.0	8.6
11	94	7.8	8.5	8.6	7.6	8.2	10.2	8.7	8.4
12	95	7.5	8.2	8.3	7.6	8.0	9.9	8.4	8.1
13	92	7.3	8.1	8.1	7.6	7.9	9.6	8.2	7.9
14	92	7.5	8.4	8.6	8.2	8.3	9.9	8.4	8.1
15	92	7.9	8.8	9.0	8.7	8.8	10.4	8.9	8.6
16	91	8.6	9.6	9.9	9.8	9.7	11.3	9.7	9.3
17	92	9.4	10.6	10.9	10.8	10.7	12.3	10.5	10.1
18	93	10.1	11.4	11.7	11.7	11.5	13.2	11.3	10.9
19	93	10.7	12.1	12.7	12.4	12.3	14.0	12.0	11.5
20	91	11.2	12.6	13.2	12.8	12.8	14.6	12.5	12.1
21	91	11.5	12.8	13.2	12.6	12.8	15.0	12.8	12.4
22	91	11.6	12.8	13.1	12.4	12.7	15.2	13.0	12.5
23	91	11.7	12.9	12.9	12.1	12.6	15.3	13.1	12.6
24	91	11.5	12.6	12.7	11.7	12.3	15.0	12.8	12.4
Total	2163								
Overall Mean Speed		9.7	10.7	10.9	10.2	10.6	12.7	10.8	10.5

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The mean  $\alpha$  (10-VRD) for the study period at S-01 is 0.05. Thus the HUBXP technique, using  $\alpha = 1/7$ , causes a 20 percent error in estimating the mean rotor disk winds. Note that  $\alpha$ 's determined from only 4 or 5 days of tower data resulted in mean speeds within 3 percent of VRD.\*

The diurnal variation of  $\alpha$  is much different than over flat terrain (Figure 4). The highest  $\alpha$  occurs in late afternoon or early evening, lowest values near sunrise. In flat terrain, however, highest  $\alpha$ 's occur about midnight, lowest values in the early afternoon (Hiester and Pennell, 1981).

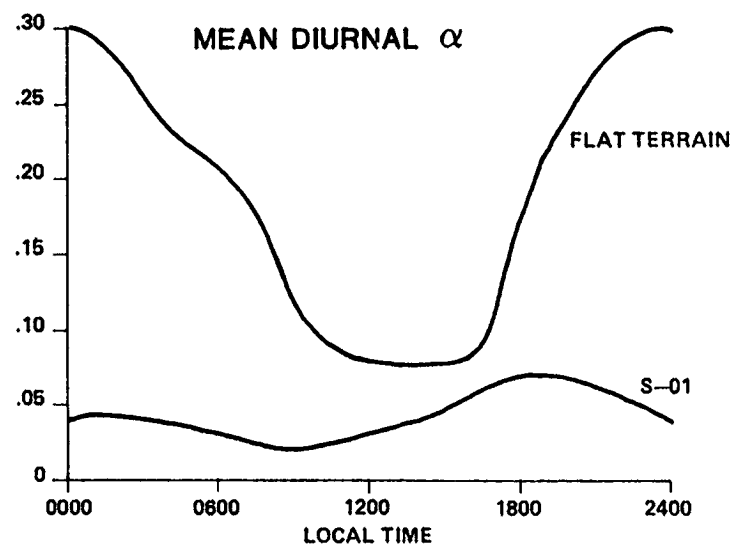


FIGURE 4. MEAN DIURNAL  $\alpha$  (10-VRD) AT S-01, SUMMER 1980 AND FOR TYPICAL FLAT TERRAIN.

\*However, the variability in individual VRD estimates are not at all described by using a single derived  $\alpha$  value (see Table 3.4.1).

### Available Power in the Wind

Site evaluations frequently include available wind power as a measure of the wind resource. The mean power is computed from the formula

$$\bar{P} = 1/2 \bar{\rho V^3}$$

where  $\bar{P}$  is the mean power,  $\bar{\rho V^3}$  is the mean product of air density ( $\rho$ ) and the cube of the wind speed.

Considerable differences result when the six different estimates of rotor disk winds are applied (Table 2).

TABLE 2. MEAN AVAILABLE POWER ( $\text{Wm}^{-2}$ )  
AT S-01, SUMMER 1980

<u>Type of Wind Speed</u>	<u>Power</u>
VRD	978
V10	739
V60	1086
HUBXP	1666
HUBK1	1037
HUBK2	931

Not unexpectedly, HUBXP is completely off the mark, being 70 percent too high. V10 is the second poorest estimator, being 25 percent too low. The other techniques are all within 10 percent of the measured value (VRD).

### Frequency Distributions of $\alpha$

There is a considerable range in  $\alpha$ -values at S-01 between 10 m and VRD (assumed height of 60 m), as shown in Figure 5. Extreme values are less frequent with higher wind speeds.

The negative shear can be particularly pronounced between 60 and 90 m. Between these two levels  $\alpha$  is often below -0.50 and has been measured to be below -1.00 under strong wind conditions (Figure 6).

Physical interpretation of these data is difficult. Apparently there is flow decoupling or flow separation; in other words, a mixing depth well below 100 m with surface winds of 10-15 mps. Onsite acoustic sounder observations during early 1981 support this conclusion.

### Frequency Distributions of Wind Speed

The frequency distributions of wind speed for the study period at S-01 are presented in Figure 7. Category breaks for wind speed are critical values of the BWT 2560 performance curve:

<u>Category</u>	<u>Classification</u>
0 - 6.3 mps	below cut-in
6.3 - 9.4 mps	cut-in to half-rated power
9.4 - 12.2 mps	half-rated power to rated power
12.2 - 26.9 mps	rated to cut-out
>26.9 mps	above cut-out

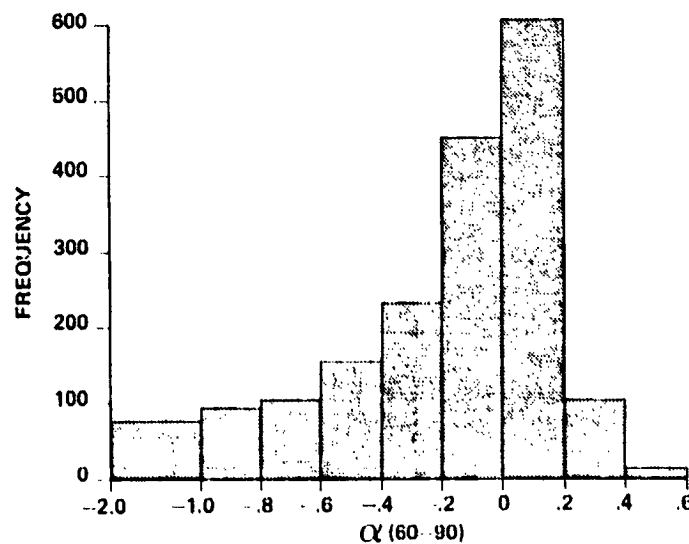
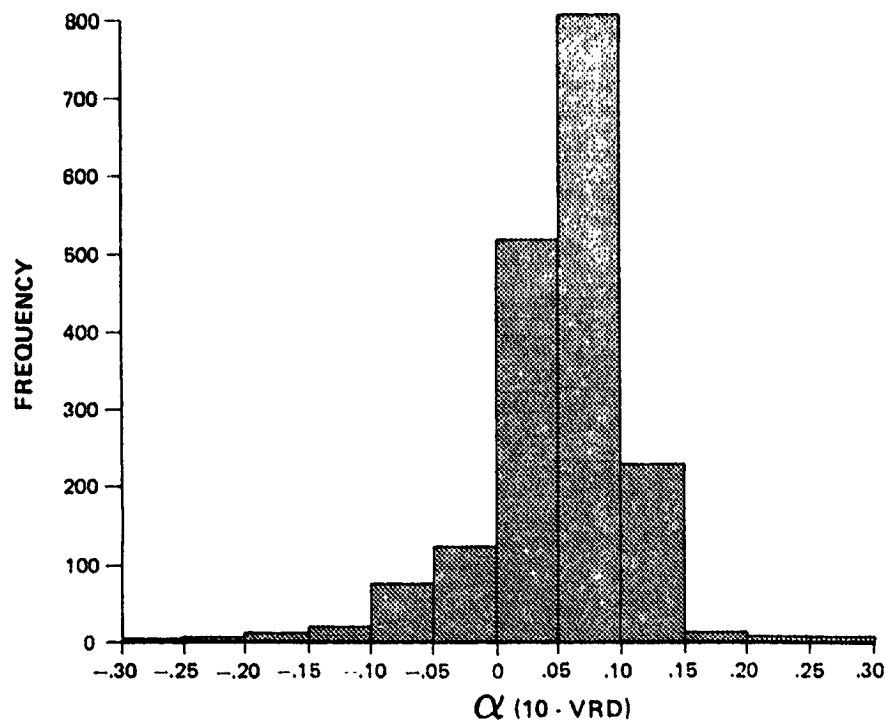
HUBK1, HUBK2, and V60 are very close to the true values. V10 is less accurate, and HUBXP grossly shifts the frequency distribution towards the higher wind speeds. It overestimates the frequency of winds above rated speed by more than 20 percent.

### BWT 2560 Power Output Simulations

Mean diurnal and overall capacity factors for a BWT 2560 are presented in Table 3. V60, HUBK1, and HUBK2 were clearly the best approximators of overall mean capacity factor at the two sites, with absolute errors ranging from 1-2 percent, relative errors from 1-3 percent.

V10 and HUBXP were far worse. The absolute error using V10 was 6 percent, the relative error 11 percent. The absolute error using HUBXP was 13 percent, or a relative error of 20 percent. Only VRD accounts for diurnal changes in the wind shear profile characteristics. Thus there is some diurnal fluctuation in the degree of error caused by the other techniques.

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FIGURES 5, 6. FREQUENCY DISTRIBUTION OF  $\alpha$  (10-VRD) AND  $\alpha$  (60-90) AT S-01, SUMMER 1980. ONLY WINDS ABOVE CUT-IN SPEED ARE CONSIDERED.

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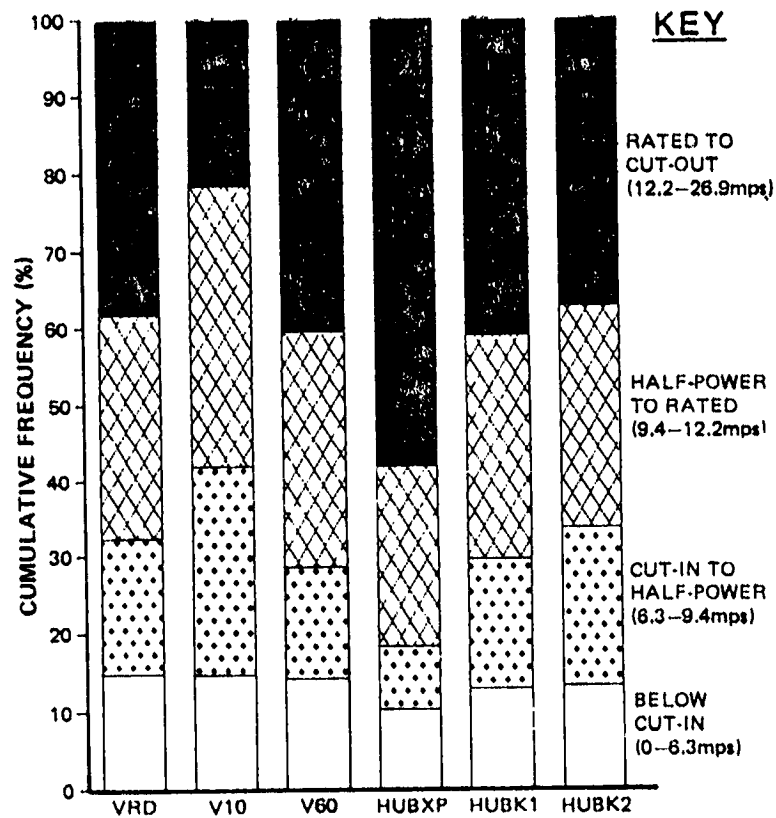


FIGURE 7. S-01 WIND SPEED FREQUENCY  
DISTRIBUTION, SUMMER 1980.

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TABLE 3. MEAN DIURNAL CAPACITY  
FACTORS (PERCENT) FOR A BWT 2560 AT S-01,  
SUMMER 1980

Hour (PST)	VRD	V10	V60	HUBXP	HUBK1	HUBK2
01	79	73	81	89	81	79
02	77	72	79	88	80	78
03	76	70	78	86	79	76
04	74	67	75	84	75	73
05	69	64	71	81	73	70
06	65	59	65	78	70	66
07	59	55	60	75	65	62
08	54	49	56	69	59	56
09	51	44	54	68	56	52
10	48	40	53	65	52	49
11	43	37	47	63	49	45
12	40	33	43	61	45	41
13	38	32	40	58	42	37
14	42	30	46	60	44	40
15	49	37	53	65	50	46
16	60	45	62	72	58	54
17	70	54	71	80	67	64
18	78	63	79	86	76	72
19	84	70	86	90	82	79
20	86	76	88	91	85	82
21	85	77	88	92	85	83
22	84	78	85	93	85	83
23	84	78	85	92	86	84
24	80	75	82	91	83	80
Overall	66	58	68	79	68	65

What do these errors really mean with respect to the cost of energy?  
A formula for computing energy cost is:

$$COE = \frac{IC \cdot FCR + LF1 \cdot AOM + LF2 \cdot AFC}{AEP}$$

where

COE = cost of energy, e.g., \$/kWh  
IC = initial system cost  
FCR = levelized fixed charge rate  
AOM = annual operation and maintenance costs  
LF1 = levelizing factor for O&M costs  
LF2 = levelizing factor for fuel costs  
AFC = annual fuel costs (equals zero for wind turbines)  
AEP = anticipated annual energy production

Thus the cost of energy is inversely proportional to the energy production.

Relative errors greater than 10 percent will certainly be significant. Thus using the 10-m wind data alone (V30) or with a 1/7 power law (HUBXP) would have caused significant errors. The 1/7 power law in particular gave very poor results, and the cost of energy calculated on that basis would be 20 percent too low.\*

#### Comparison of Winter and Summer Vertical Profiles

The mean vertical profiles at both sites change seasonally with similar wind speeds and directions (Figure 8). The mean  $\alpha$  (10-VRD) was .03 higher in winter than summer for westerly winds of power-producing strength. This seasonal fluctuation results from the different wind-driving forces of the two seasons--mesoscale sea breeze in summer, synoptic in winter.

Also, strong winds blow from several directions during winter. Additional errors would thus be introduced if a summer  $\alpha$  were applied to 10-m data from other seasons and/or wind directions.

#### SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Considerable errors in wind speed and power generation estimates were found at Site S-01 with certain techniques for estimating effective rotor disk winds, as summarized below (Table 4). In particular, the 1/7 power law (HUBXP) applied to 10-m data caused very large errors and should not be used.

\*The study period comprised only the summer season, and thus does not simulate annual energy production. The concept is still quite valid, though.



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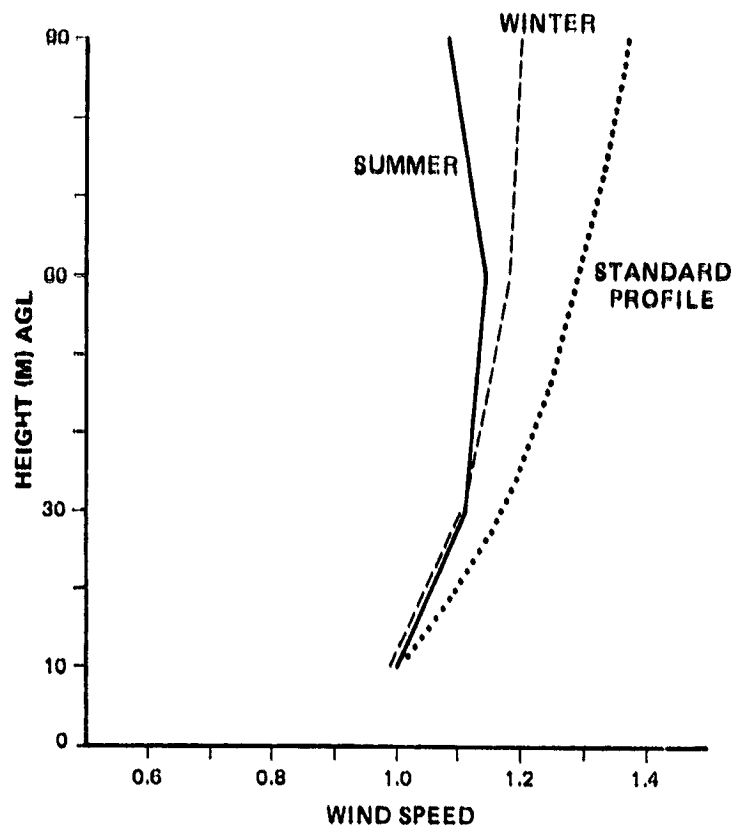


FIGURE 8. MEAN PROFILE CHARACTERISTICS AT S-01 FOR WESTERLY WINDS ABOVE CUT-IN SPEED. CURVES ARE NORMALIZED TO 10-M SPEED.

TABLE 4. SUMMARY OF ERRORS (IN PERCENT) IN SPECIFYING WIND ENERGY PARAMETERS CAUSED BY DIFFERENT MONITORING STRATEGIES<sup>a</sup>

	<u>V10</u>	<u>V60</u>	<u>HUBXP</u>	<u>HUBK1</u>	<u>HUBK2</u>
Mean speed <sup>b</sup>	-9	3	20	2	-1
Mean power <sup>b</sup>	-24	11	70	6	-5
Percent hours at rated power <sup>c</sup>	-17	2	20	3	-1
Mean capacity factor <sup>b</sup>	-12	3	20	3	-1

<sup>a</sup>VRD used as control variable

<sup>b</sup>Relative errors (actual error divided by VRD mean)

<sup>c</sup>Actual percentage error

In conclusion, the 60-m (hub height) wind was the most accurate technique, even though S-01 had a mean reversal in shear with maximum mean winds at that level. In practice one would probably not measure only at this level to estimate the wind resource, but these results do imply hub height data should be adequate for estimating the overall performance of large wind turbines.

While the 10-m wind data alone were not very accurate, the addition of even a few days' worth of vertical profile measurements greatly improved the estimates. However, one must be very careful about making generalizations from these results. (Only one season with one dominant wind direction was considered here.) The amount of random data needed to predict the vertical profile characteristics with sufficient confidence will surely vary from site to site and is hard to specify in advance. Further, intermittent monitoring strategies (e.g., kites, Doppler acoustic sounder) run a high risk of missing extreme conditions, such as severe wind speed and/or direction shears.

By far the most important conclusion of this study is that gross errors in estimating rotor disk wind speeds and energy production can result if measurements are limited to the 10-m level. As pointed out earlier, most wind energy sites will be in complex terrain, and it is absolutely crucial to obtain measurements up to at least hub height and preferably to the top of the rotor disk.

#### REFERENCES

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- Mahrt, L., and R. C. Heald, 1979: Analysis of strong nocturnal shears for wind machine design (Progress Report). Oregon State University. DOE publication DOE/ET/23116-79-1.
- Munn, R. E., 1973: Descriptive Meteorology. Academic Press, Inc. New York, pp. 63-65.

## QUESTIONS AND ANSWERS

R. L. Simon

From: B. Liebowitz

Q: Clarification of the use of the intermittent data that was used: was the  $\alpha$  obtained using intermittent data treated as a constant between samplings for the month to extrapolate from 10(m) to hub height?

A: Wind speed at 10 m was extrapolated to hub height with an alpha derived from 5 random days of 90-m tower data, using only the hours between 0500 and 2000 PST when the 10-m wind speed exceeded 4 mps. This exponent  $\alpha$  was computed slightly differently. The usual method is to use the 10-m and 60-m wind speeds to get the power law exponent between those levels. However, we replaced the 60-m wind speed with effective rotor disk wind speed (VRD), since VRD is the direct estimate of the rotor disk wind speed.

From: M. Sacarmy

Q: Were you doing any studies on change of gust with height?

A: Not really. We kept the standard deviation of the collected velocities for various intervals up to the 1 hr averages, and so we could reconstruct the power spectral densities if we had to.

From: D. S. Renné

Q: Over what averaging period were the  $\alpha$ 's computed?

A: 1 hr averages.

From: K. Foreman

Q: Did your calculation of rotor disk power account for the differences in free air capture area relative to the physical rotor disk area? (You know, of course, that optimally the capture area is (2/3) the rotor area.)

A: Yes, indirectly. We were trying to get the best number to represent what the wind turbine would "see" WRT machine performance curves. It is thus the wind speed that would be there if no turbine were there.

From: M. F. Merriam

Q: Do you believe that kite measurements are accurate enough so that your conclusions are correct?

A: Yes.

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LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Current Large Wind Turbine Systems

Session Chairman - T. P. Cahill (NASA LeRC)

"Performance and Load Data From the Mod-0A and Mod-1 Wind Turbine Generators"

D. A. Spora  
D. C. Janetzko  
(NASA LeRC)

"Operating Experience with Four 200-kW Mod-0A Wind Turbine Generators"

A. G. Birchenough  
A. L. Saunders  
T. W. Nyland  
R. K. Shaltens  
(NASA LeRC)

"Experience and Assessment of the DOE/NASA Mod-1 2000 kW Wind Turbine Generator at Boone, North Carolina"

J. L. Collins  
R. K. Shaltens  
(NASA LeRC)  
R. H. Poor  
R. S. Barton  
(General Electric Company)

"Description of the 3 MW SWT-3 Wind Turbine at San Geronio Pass, California"

S. C. Rybak  
(The Bendix Corporation)

"Operational Experience on the MP-200 Series Commercial Wind Turbine Generators"

M. B. Rose  
(WTG Energy Systems, Inc.)

PERFORMANCE AND LOAD DATA FROM MOD-OA AND  
MOD-1 WIND TURBINE GENERATORS

David A. Spera and David C. Janetzke  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio

ABSTRACT

Experimental data, together with supporting analysis, are presented on the power conversion performance and blade loading of large, horizontal-axis wind turbines tested at electric utility sites in the U.S. Four turbine rotor configurations, from 28 to 61 meters in diameter, and data from five test sites are included. Performance data are presented in the form of graphs of power and system efficiency versus free-stream wind speed. Deviations from theoretical performance are analyzed statistically. Power conversion efficiency averaged 0.34 for all tests combined, compared with 0.31 predicted. Round blade tips appeared to improve performance significantly. Cyclic blade loads were normalized to develop load factors which can be used in the design of rotors with rigid hubs.

INTRODUCTION

This paper presents experimental data and supporting analysis of the power conversion performance and blade loading of large, horizontal-axis wind turbines tested at electric utility sites in the U.S. These tests were conducted by the National Aeronautics and Space Administration (NASA) as part of the federal wind energy program administered by the Department of Energy (DOE). The principal objectives of this work are (1) to provide performance and load test data for wind turbine design, (2) to evaluate the PROP-L2 computer program for predicting the efficiency of propeller-type wind turbines, and (3) to examine a proposed energy method for testing wind turbine system performance.

Data from tests of four turbine rotor configurations are analyzed in this paper. The airfoil shapes and dimensions of each configuration are listed in Table I, and their planforms are illustrated in Figure 1. The rotors studied had two blades each and ranged in diameter from 28 to 61 meters. Thickness-to-chord ratios at 75 percent of span varied from 0.156 to 0.240. Two NACA airfoils and four skin materials were tested. One configuration had semi-circular blade tips. Blades in the other three configurations had square tips.

As shown in Table II, test data have been grouped according to the configuration of the rotor and the turbine shaft speed into six test series. Each of these series is a combination of several data records, one to six hours long, which were selected to represent a variety of operating conditions.

Data on test installations are also given in Table II. Rotor configurations 1, 2, and 3 were tested on Mod-0A machines, while configuration 4 was tested on the larger Mod-1 system (ref. 1). These experimental wind turbines are of the "first generation" type (ref. 2), with the following design characteristics in common: Two blades, fully pitchable for power control; rotor hub rigidly attached to the turbine shaft; turbine rotor located downwind of a stiff truss tower; parallel-axis gearbox with a single speed ratio; synchronous AC generator; and active yaw control.

Preliminary performance and load data measured on the Mod-0A and Mod-1 systems were presented in References 3 to 8. The data contained in this paper significantly extend those reported earlier, by including additional rotor configurations and wind turbine test installations, moderately long operating periods and additional statistical analysis. Therefore, the performance and load data presented here can be regarded as typical of the first generation of large, horizontal-axis wind turbines.

## PROCEDURE

### Test Installation and Data

Details of the DOE/NASA wind turbine test installations, instrumentation, and data acquisition system have been presented previously (ref. 9 and 10, for example), so only a brief discussion will be given here. Figure 2 illustrates the test installation at Clayton, New Mexico, which is typical of all the installations listed in Table II. At each test site, an auxiliary anemometer tower is located several rotor diameters from the turbine tower, in the direction of the prevailing wind. Signals from a variety of transducers located throughout the test system are recorded on analog tape, digitized, and then processed to produce statistical information and graphical displays. Data are recorded automatically during normal operation of the wind turbine generator as a powerplant on the electric utility system.

The four parameters of specific interest in this study of turbine performance and loads are as follows:

1. Free-stream wind speed at hub elevation,  $V_0$ , measured by an anemometer on the auxiliary tower at the elevation of the turbine axis (Station 0, fig. 2). Averaging time was selected as 30 seconds and the anemometer length constant was 1.5 meters. Wind data were purposely limited to measurements from a single anemometer, because one free-stream anemometer is often all that is available.
2. Output electrical power,  $P_3$ , measured at the generator terminals (Station 3, fig. 2).

3. Two components of cyclic bending load on the blade root,  $\delta M_y$  and  $\delta M_z$ . Cyclic load is a typical measure of fatigue loading and is calculated for each turbine revolution as follows:

$$\text{Flatwise (out-of-plane): } \delta M_{y,i} = 0.5(M_{y,\max} - M_{y,\min})i \quad (1a)$$

and

$$\text{Chordwise (in-plane): } \delta M_{z,i} = 0.5(M_{z,\max} - M_{z,\min})i \quad (1b)$$

in which  $i$  is the rotor revolution number and max and min designate the extreme values of the load measured during that revolution.

### Theoretical Output Power

Theoretical turbine power, as a function of free-stream wind speed, was calculated by means of a modified version of the commonly-used PROP FORTRAN computer program (ref. 11), designated as PROP-L2. Recent tests on wind turbine rotors in the stalled condition (ref. 12) indicated the need for improved aerodynamic modeling in the basic PROP program. In the PROP-L2 version, aerodynamic losses at square tips are included within the blade-element algorithms by introducing the following two modifications:

1. Correcting reference lift and drag curves for planform aspect ratio (refs. 12 and 13).
2. Using "smooth" airfoil properties, instead of "rough" or "half-rough," as in previous studies (ref. 8, for example).

A comparable theory for the aerodynamic losses at rounded blade tips has not yet been developed. Therefore, test data for configuration 3R, with semi-circular tips, are compared with theoretical calculations for square-tipped blades, to identify differences which may be attributable to tip shape.

In addition to the PROP-L2 computer program for turbine power, a model for losses in the power train is required before generator output can be predicted. A general power-train loss model which was developed for this study is as follows:

$$P_{23} = P_3 - P_2 = -aP_{3,r} - (b+s)P_2 \quad (2)$$

in which

$P_{23}$  power-train loss, kW

$P_2, P_3$  turbine and generator output power, respectively, kW

$P_{3,r}$  rated output power, kW

$a, b$  empirical constants

s            slip ratio

For the Mod-0A power trains, a is 0.055, b is 0.040, and s is 0.025. For the Mod-1 system, a is 0.027, b is 0.059, and s is zero.

### Energy Method for Evaluating Performance

The performance of the wind-turbine-generator system can be evaluated by measuring either its power conversion efficiency or its energy conversion efficiency. Previous studies have used power as the primary performance parameter, with energy (and particularly annual output energy) as a derived parameter. Data have generally been statistically analyzed by the "method of bins" (refs. 8 and 14). An alternative method has been developed for this study, in which energy is the primary parameter, power is a derived parameter, and the required amount of statistical analysis is greatly reduced or eliminated.

The energy method for evaluating the performance of wind turbine systems appears to offer advantages of simplicity and repeatability, compared with the method of bins. Also, evaluation of theoretical methods for predicting performance may be more relevant to operation when comparisons are made on the basis of energy capture rather than instantaneous power. A committee of the American Society of Mechanical Engineers is now evaluating the energy method as a basis for a performance test code for wind turbine generators.

To apply the energy method, the following steps are performed:

1. Divide the test period into time increments,  $\Delta t$ . Each time increment should be 5 to 10 times as long as the longest wind transit time from the free-stream anemometer to the turbine (fig. 2). Time increments of this length reduce time correlation errors but still permit comparison of test data with steady-state theoretical power curves. In this study time increments were 10 minutes long.
2. During each time increment measure the time history of the free-stream wind speed at the turbine midline elevation,  $v_o(t)$ . Calculate the mean wind speed,  $V_o$ , the increment in wind energy flux,  $\Delta e_o$ , and the mean wind power flux,  $p_o$ , for each time increment, as follows:

$$V_o = \frac{1}{\Delta t} \int_{\Delta t} v_o(t) dt, \quad \text{m/s} \quad (3a)$$

$$\Delta e_o = \frac{\rho}{2} \int_{\Delta t} [v_o(t)]^3 dt, \quad \text{W-s/m}^2 \quad (3b)$$

and

$$p_o = \Delta e_o / \Delta t, \quad \text{W/m}^2 \quad (3c)$$



3. For each time increment measure the corresponding increment in electrical output energy,  $\Delta E_3$ . Calculate increments in output energy flux,  $\Delta e_3$ , mean output power,  $P_3$ , and the mean output power flux,  $p_3$ , as follows:

$$\Delta e_3 = \Delta E_3 / A, \quad \text{W-s/m}^2 \quad (4a)$$

$$P_3 = \Delta E_3 / \Delta t, \quad \text{W} \quad (4b)$$

and

$$p_3 = P_3 / A, \quad \text{W/m}^2 \quad (4c)$$

in which  $A$  is the area of the surface swept by the turbine rotor, as projected on a vertical plane.

4. For each time increment, calculate the system energy conversion efficiency, as follows:

$$\eta_3 = \Delta e_3 / \Delta e_0 = p_3 / p_0 \quad (5)$$

5. Evaluate system performance by means of data from steps 2 to 4. Evaluation may be based on any or all of the following: (a) Power curves, such as  $P_3$  and  $p_3$  versus  $V_0$ , (b) efficiency curves, such as  $\eta_3$  versus  $V_0$ , and (c) statistical analysis of deviations from available theory.

## RESULTS AND DISCUSSION

### Power Conversion Performance

Performance test results for each of the four rotor configurations described in Table I are presented in the following three formats:

First, Figures 3 to 6 show graphically the variation of output power and system efficiency with wind speed for each configuration. Secondly, summaries of test conditions, measured mean power and efficiency, and theoretical mean power and efficiency are listed in Table III. Finally, Table IV contains the results of a statistical analysis of deviations between the test data and theoretical performance.

The test series during which performance data were taken are those listed in Table II as series 1.1, 2.1, 3.1R, and 4.1. Only blade load data from test series 1.2 and 2.2 are included in this study. Performance test runs were selected to emphasize wind conditions below rated, for which efficiency data are most significant. However, no attempt was made to select periods of steady wind. Instead, the variability of the wind power source was included so that these data would be typical of automatic, unattended wind turbine operations in below-rated winds. In all cases, the

experimental wind turbine was the only wind power unit on the test site.

Figures 3 to 6 present comparisons between theoretical and experimental performance. The theoretical power curves are for "site standard" conditions, in which air density is equal to the U.S. Standard Atmosphere density for the site altitude. Test data were also adjusted to site standard conditions, with the exception of test series 2.1. Atmospheric pressure data were not available for this test series. Each data point represents average performance during a 10-minute period of operation under automatic control.

While some qualitative comparisons between theory and experiment can be made from these figures, the amount of scatter is such that statistical analysis is required. This scatter is typical of tests on large wind turbines and indicates that wind conditions over the turbine swept area and those sampled by the free-stream anemometer were not completely correlated. As expected, scatter of the efficiency data is greater than that of the power data, because wind speed correlation errors are amplified when the speed is cubed to calculate wind power flux.

Another commonly observed phenomenon is shown clearly in Figure 4(a) by the data at the transition from below-rated to above-rated wind speeds. Data in this region usually fall below the theoretical "corner", because average power is always lowered whenever the power control system is active. Nevertheless, inspection of Figures 3 to 6 indicate that (1) zero-power or cut-in wind speeds were predicted within 0.5 meter per second, (2) slopes of the theoretical power curves were in general agreement with the test data, (3) test data points for configuration 3R (the 14 meter wood/composite blades with semi-circular tips) almost always exceeded theoretical performance, and (4) test data verified the predicted highest efficiency of rotor configuration 4.

Table III summarizes the results of these four series of performance tests in quantitative terms. For example, test series 1.1 was composed of data records totaling 11 hours in length, with a mean wind speed of 7.7 meters per second, equivalent to a mean tip speed ratio of 10.5. During this period, the mean wind power flux at the turbine hub elevation was 270 Watts per square meter. Mean electrical output power flux was measured at 90 Watts per square meter. This indicates an average system efficiency of 0.33, the same as the theoretical value. Similarly, during test series 2.1, the mean power conversion efficiency was equal to the theoretical efficiency.

The semi-circular tips on the blades in configuration 3R appear to have increased the performance of these airfoils significantly, compared to predictions for the same blades with square tips. Based on the results of test series 1.1 and 2.1, the mean efficiency of rotor configuration 3 with square tips would not be expected to

exceed 0.26. However, with semi-circular tips this rotor configuration operated with a mean efficiency of 0.32. This indicates an improvement of more than 20 percent in energy production during operation below rated power. To verify this improvement, tests of configuration 3 blades with square tips are planned. This amount of improvement, however, may be limited to low aspect ratio blades. Further tests are required to evaluate the effects of tip shape on the performance of blades with higher aspect ratios.

If the results of all four series of performance tests are combined by weighted averaging into one data set as shown in the last line of Table III, this set would represent a sample of current experience with large, first-generation, propeller-type rotors. Including the effects of different tips and site roughnesses, an overall efficiency of 0.34 has been achieved in predominantly below-rated winds. This compares very well with a theoretical power conversion efficiency of 0.31 for the same wind conditions.

Statistical analysis of deviations between the performance test results and predictions made using the PROP-L2 computer program are summarized in Table IV. The mean deviation of the samples from the common base of the theory shows a performance advantage of more than 9 percent of rated power for configuration 3R over the composite performance of the three other configurations. This difference in performance has been attributed to the difference in tip shape although this has yet to be verified. Standard deviations for the four test series are remarkably consistent at 5 to 6 percent of rated power. This indicates that the scatter observed in Figures 3 to 6 is repeatable and acceptable for purposes of performance evaluation.

By analyzing deviations between test and theory, the theoretical power curve can be adjusted to serve as a lower bound on predicted performance. The size of the adjustment depends on the desired confidence in the predicted lower bound. Standard statistical analysis methods can be used to calculate the adjustment, as discussed in Reference 8. As shown in the last column of Table IV, if the predicted mean power flux of a rotor with square tips is reduced by 3 Watts per square meter, there is a 0.999 confidence level that the mean power during long-term tests will not be less than this reduced value. For blades like those of configuration 3R, with semi-circular tips, an increase in the theoretical power flux of 26 Watts per square meter is consistent with a 0.999 lower bound on mean performance. However, additional tests are required to support this latter conclusion.

To summarize the results of the performance testing in this study, the wind turbine generators converted about one-third of the incident wind energy to electricity, the PROP-L2 computer program was verified as a performance prediction method, and lower bounds on performance were estimated.

### Blade Bending Load Data

Dynamic loads sustained by rotor blades on large, horizontal-axis wind turbines were measured during all six test series listed in Table II. The load data obtained are typical of first-generation wind turbines, which are characterized by rigid hubs, rotors located downwind of truss towers, and full-span pitch controls. Load test results are shown in Figures 7(a) to 7(d) in the form of cumulative probability distributions useful for fatigue life analysis. Cyclic flatwise and cyclic chordwise load components are given for each test series. Component directions are referred to the chord line of the airfoil section at 75 percent of span. This chord line is nominally in the plane of rotation during operation in winds of below-rated speed. All loads were measured in the root areas of the rotor blades, at radial distances between 5 and 10 percent of the blade span.

As shown by the straight lines fitted to the test data, cyclic loads were found to have log-normal probability distributions within each test series. The slopes of the curve-fit lines are proportional to the log-standard deviations of the data. Steeper slopes may be attributed to larger variations in wind speed, wind shear, and turbulence during the test series.

Table V summarizes the significant results of this experimental study of blade bending loads. In addition to information on test series duration and mean wind speed, cyclic flatwise and cyclic chordwise bending loads are listed for two percentiles of interest: 50 and 99.9. The 50th percentile load is useful for calibrating theoretical load prediction methods which may not include turbulent winds and operating transients (ref. 15). However, the value of the 50th percentile load for purposes of fatigue life analysis is small because fatigue damage cannot be tolerated at this percentile load in a long-life design. Of more use in life prediction is the 99.9th percentile load. A design fatigue life of  $10^6$  cycles or more is often required at this load level. Operating load limits for several of the rotor configurations tested in this study were set at predicted 99.9th percentile levels.

The cyclic load data in Table V have been normalized to remove differences in scale, in order to derive general load factors useful for design. A convenient reference for the flatwise load components was found to be the difference between the theoretical steady aerodynamic flatwise bending load at rated wind speed and that at the zero-power (cut-in) wind speed. The reference for chordwise loads was the gravity bending moment measured with the blade horizontal. All reference loads were determined for the radial stations at which the cyclic loads were measured. Load factors were calculated by dividing test loads by the reference loads for the test series.

Variations in flatwise cyclic load factors among the six test series were relatively small, considering the wide variation in rotor

configurations. This tends to verify the assumption that the selected reference load contains the key parameters governing cyclic flatwise blade loading. Flatwise load factors were smallest for test series 1.2 which had the lowest mean wind speed and was conducted at a location with low terrain roughness (Table II). Low terrain roughness usually produces low average wind turbulence. Larger flatwise load factors generally correlated with higher wind speeds and locations with rougher terrain. Averaging the flatwise load test results for the six series gives factors of 0.24 and 0.73 for the 50th and 99.9th percentile cyclic loads, respectively.

Chordwise cyclic load factors averaged 1.11 and 1.46 for the 50th and 99.9th percentile loads, respectively. While it is convenient for design purposes to reference chordwise loads to the dominant gravity load, the components of these load factors in excess of 1.00 have been found to correlate with flatwise cyclic bending, rather than with blade mass properties (ref. 15). Again, variations in chordwise load factors were small for each percentile, although the actual chordwise cyclic loads varied by more than an order of magnitude.

In summary, blade cyclic load spectra for both flatwise and chordwise bending can be estimated for first-generation, horizontal-axis wind turbine blades by applying the load factors and reference loads given in Table V.

## CONCLUSIONS

This study has provided a set of test data on the power conversion performance and dynamic blade loading typical of first-generation, horizontal-axis wind turbine generators. The following conclusions are drawn from analysis of these test data:

1. The mean power conversion performance of four test rotor configurations equaled or exceeded system efficiencies as predicted by means of the PROP-L2 computer program.
2. During 64 hours of automatic operation in primarily below-rated winds, the composite system efficiency of the four rotor configurations was 0.34, which compares favorably with a theoretical efficiency of 0.31 for the measured wind conditions.
3. The proposed energy method for analyzing performance test data provided a practical solution to problems presented by wind turbulence and time-varying test data. Results were found to be repeatable for a variety of test rotors and test installations.
4. Blade cyclic load spectra exhibited log-normal distributions in all cases studied.

5. Load factors and reference loads have been derived with which blade fatigue loads can be estimated for design purposes.

#### UNIT CONVERSION FACTORS

1 m	=	3.28 ft	1 rad/s	=	9.55 rpm
1 m <sup>2</sup>	=	10.76 ft <sup>2</sup>	1 kN-m	=	738 lb-ft
1 m/s	=	2.24 mph	1 kg/m <sup>3</sup>	=	0.00197 slug/ft <sup>3</sup>

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TABLE I  
AIRFOIL GEOMETRY OF WIND TURBINE ROTOR CONFIGURATIONS

Spanwise coordinate		Chord	Thickness to chord ratio	Twist (towards feather) deg	Skin material
m	percent	m			
(a) Configuration 1 (NACA-23000 series airfoil coned 7 deg)					
1.22	6	1.37	0.440	31.7	Aluminum
2.86	15	1.37	0.372	21.7	Aluminum
4.76	25	1.37	0.291	14.0	Aluminum
5.72	30	1.31	0.250	11.3	Aluminum
9.53	50	1.06	0.212	4.0	Aluminum
14.29	75	0.76	0.165	0	Aluminum
19.05	100	0.46	0.120	-2.0	Aluminum
(b) Configuration 2 (NACA 23000 series airfoil coned 7 deg)					
4.27	22	1.58	0.298	4.2	Wood
14.29	75	0.94	0.156	0	Wood
19.05	100	0.64	0.088	-2.0	Wood
(c) Configuration 3R (NACA 23000 series airfoil coned 7 deg)					
4.27	30	1.52	0.310	0	Wood
8.18	58	1.52	0.240	0	Wood
10.57	75	1.36	0.240	0	Wood
12.47	89	1.24	0.240	0	Fiberglass
13.51	96	1.17	0.217	0	Fiberglass
14.10	100	0	0	0	Fiberglass
Semi-circular tips, beveled both sides, from 13.51 m to 14.10 m					
(d) Configuration 4 (NACA 4400 series airfoil coned 9 deg)					
3.07	10	3.66	0.333	8	Steel
23.05	75	1.64	0.165	0	Steel
30.73	100	0.86	0.100	-3	Steel



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TABLE II  
WIND TURBINE ROTOR TEST SERIES AND INSTALLATIONS

Rotor config.	Test series no.	Turbine rotor data			Test installation data				
		Shaft speed rad/s	Blade tip speed m/s	Swept area m <sup>2</sup>	Wind energy system	Rated power kW	Location	Hub elev. m	Relative terrain roughness
1	1.1	4.3	81	1123	Mod-OA	200	Clayton, NM	1566	medium
	1.2	3.3	63	1123	Mod-OA	150	Culebra, PR	110	low
2	2.1	4.3	81	1123	Mod-OA	200	Kahuku, HI	137	low
	2.2	3.3	63	1123	Mod-OA	150	Block Is., RI	44	high
3R	3.1R	4.3	60	615	Mod-OA	200	Clayton, NM	1566	medium
4	4.1	3.7	111	2894	Mod-1	2000	Boone, NC	1387	high

TABLE III  
SUMMARY OF POWER CONVERSION PERFORMANCE OF  
FOUR DOE/NASA HORIZONTAL-AXIS WIND TURBINES

Test series no.	Test period hr	Free-stream wind input measured at hub elevation			Mean output power flux at generator		Mean power conversion efficiency	
		Mean wind speed m/s	Mean tip speed ratio	Mean input power flux W/m <sup>2</sup>	Theory [a] W/m <sup>2</sup>	Test W/m <sup>2</sup>	Theory [a]	Test
1.1	11	7.7	10.5	270	89	90	0.33	0.33
2.1	20	8.2	9.9	381	112	111	0.29	0.29
3.1R[b]	22	9.2	6.5	537	141	172	0.26	0.32
4.1	11	10.2	10.9	584	238	250	0.41	0.43
Data set	64	8.8	9.0	450	140	152	0.31	0.34

[a] PROP-L2 computer program, with square-tip loss model

[b] Semi-circular tips on blades; all other blades have square tips

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TABLE IV  
DEVIATION OF TEST OUTPUT POWER FLUX FROM THEORY,  
FOR FOUR DOE/NASA HORIZONTAL-AXIS WIND TURBINES

Test series no.	No. of samples	Mean deviation of samples		Standard deviation of samples		Lower bound on mean deviation (0.999 conf.)	
		W/m <sup>2</sup>	% of rated	W/m <sup>2</sup>	% of rated	W/m <sup>2</sup>	% of rated
(a) Blades with square tips							
1.1	68	1	0.6	11	6.2	-3	-1.7
2.1	119	-1	-0.6	9	5.1	-3	-1.7
4.1	65	12	1.7	39	5.6	-3	-0.4
Data set	252	3	0.3	7	5.5	-3	-1.2
(b) Blades with semi-circular tips (theory for square tips)							
3.1R	131	31	9.5	19	5.8	26	8.0

TABLE V  
SUMMARY OF BLADE CYCLIC LOAD TEST DATA  
FROM SIX DOE/NASA HORIZONTAL-AXIS WIND TURBINES

Test series	Test period  10 <sup>3</sup> rotor revs.	Mean wind speed  m/s	Flatwise cyclic bending loads [a]			Chordwise cyclic bending loads [a]		
			Ref. load [b]	Load factor, by percentile		Ref. load [c]	Load factor, by percentile	
				50	99.9		50	99.9
1.1	102	9.3	134	0.22	0.85	61.6	1.10	1.48
1.2	86	6.1	118	0.17	0.53	61.6	1.04	1.36
2.1	126	8.8	152	0.24	0.74	68.0	1.12	1.51
2.2	77	6.6	134	0.31	0.75	56.5	1.15	1.58
3.1	126	7.1	108	0.22	0.67	70.5	1.13	1.39
4.1	40	8.8	1177	0.44	0.97	739.	1.08	1.50
Data set	557	7.7	NA	0.24	0.73	NA	1.11	1.46

- [a] 0.5 (max load - min load) per rotor revolution, measured at 5% to 10% of span  
[b] Steady aerodynamic bending moment change from zero power to rated (PROP-L2 program)  
[c] Gravity bending moment, blade horizontal (measured)

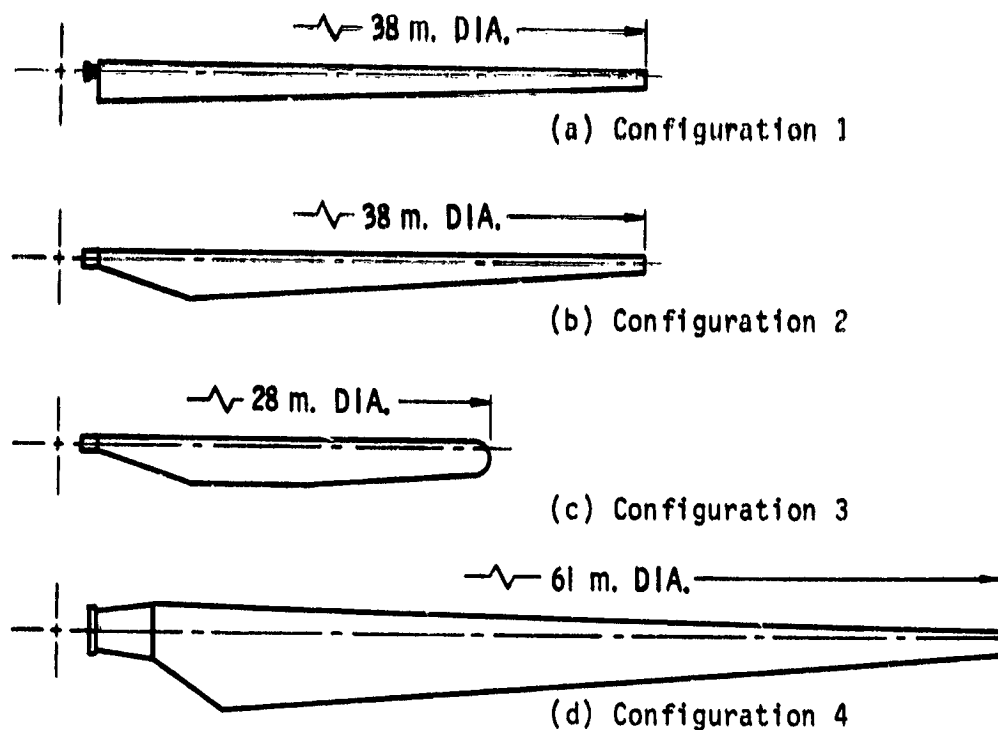


Figure 1. -- Planforms of wind turbine blades tested for power conversion performance and structural loads.

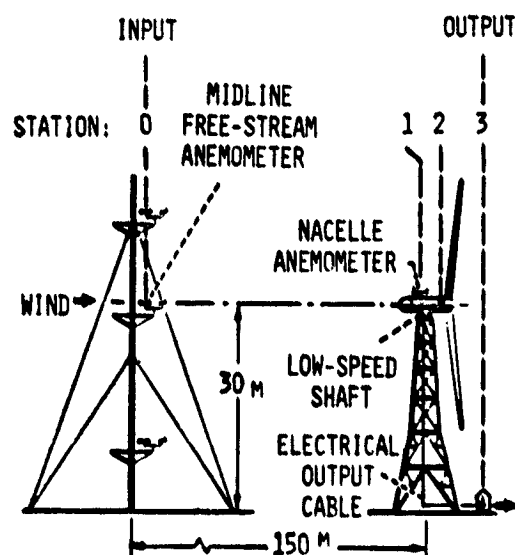
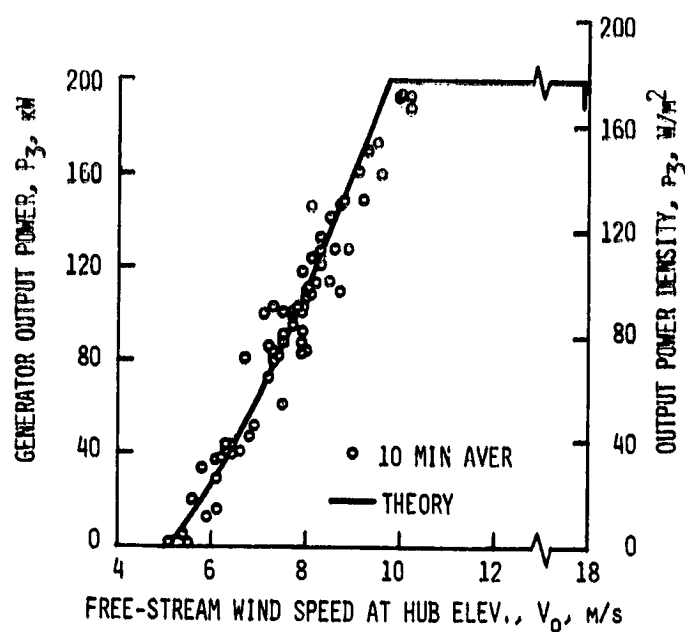
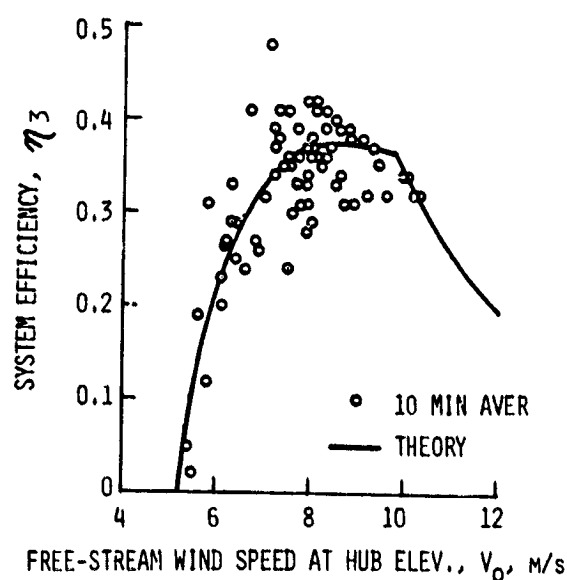


Figure 2. -- Typical performance test installation, showing the Mod-0A 200 kW wind turbine generator, the anemometer tower, and measurement stations at Clayton, New Mexico

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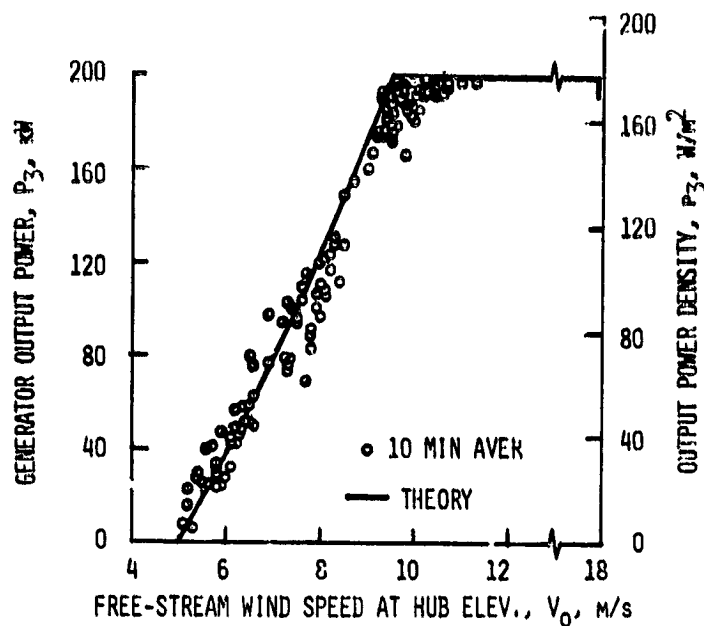
(a) Output power (air density =  $1.05 \text{ kg/m}^3$ )



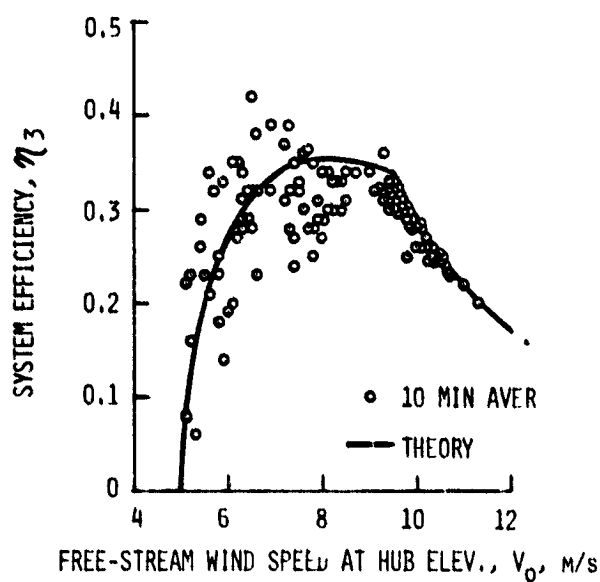
(b) System efficiency

Figure 3. -- Test series 1.1 power conversion performance, compared with theoretical performance (Mod-0A aluminum blades at Clayton, New Mexico).

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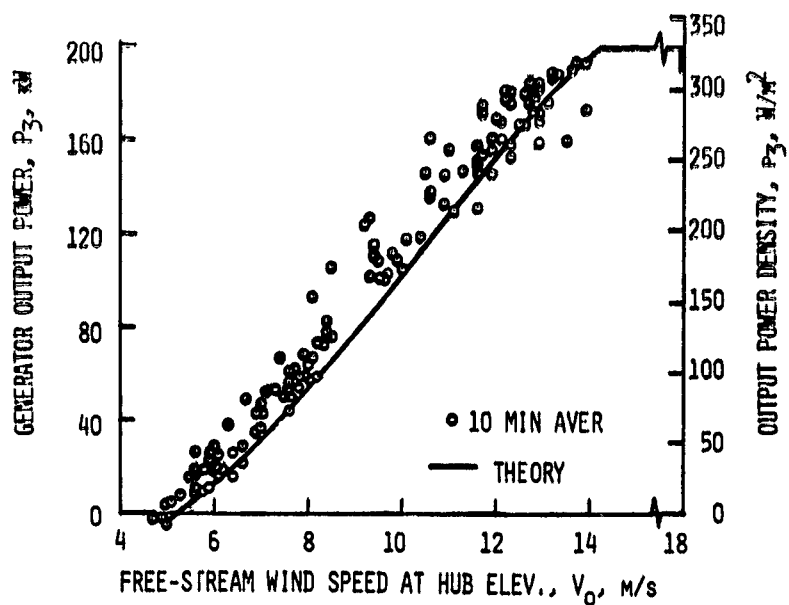
(a) Output power (air density =  $1.21 \text{ kg/m}^3$ )



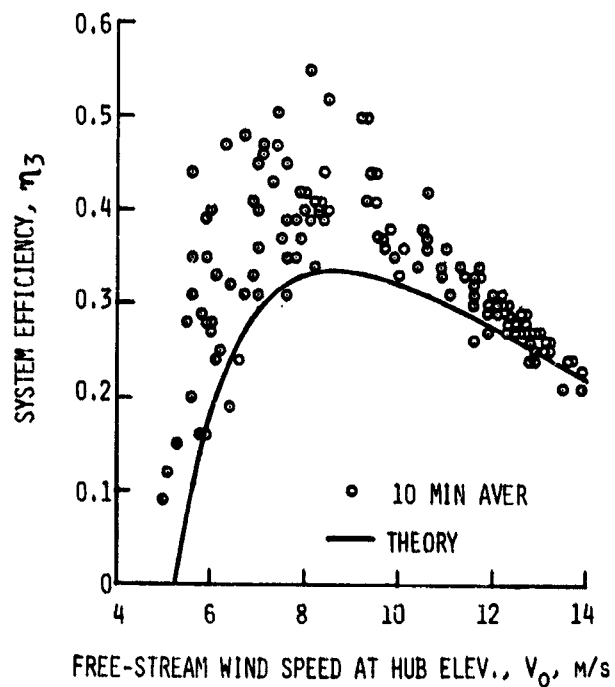
(b) System efficiency

Figure 4. -- Test series 2.1 power conversion performance, compared with theoretical performance (Mod-OA wood blades at Kahuku, Hawaii).

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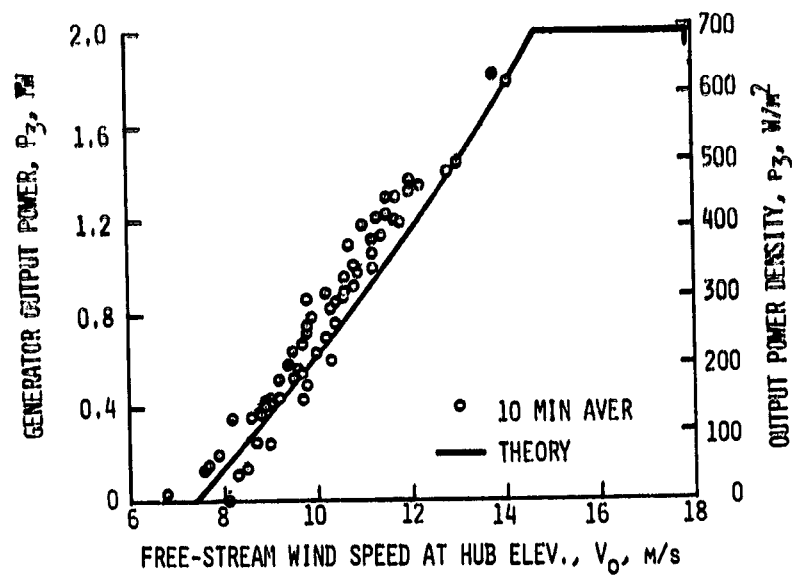
(a) Output power (air density =  $1.05 \text{ kg/m}^3$ )



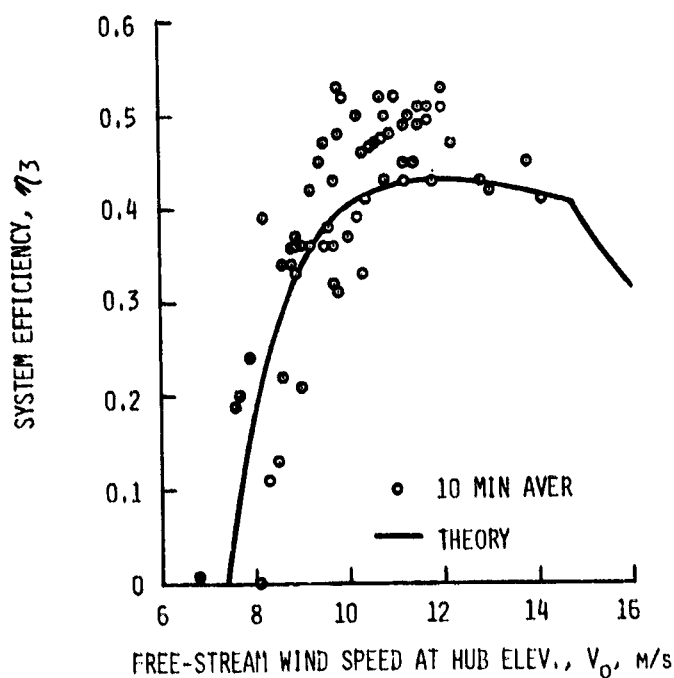
(b) System efficiency

Figure 5. -- Test series 3.1R power conversion performance, compared with theoretical performance (Mod-OA wood/fiberglass blades with semi-circular tips at Clayton, New Mexico).

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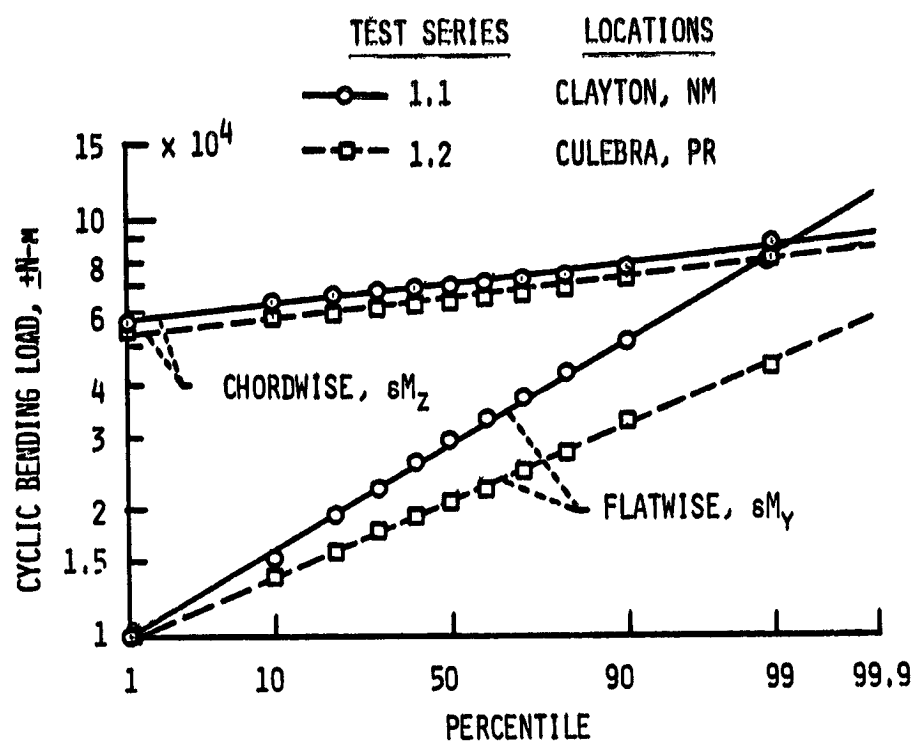


(a) Output power (air density =  $1.07 \text{ kg/m}^3$ )

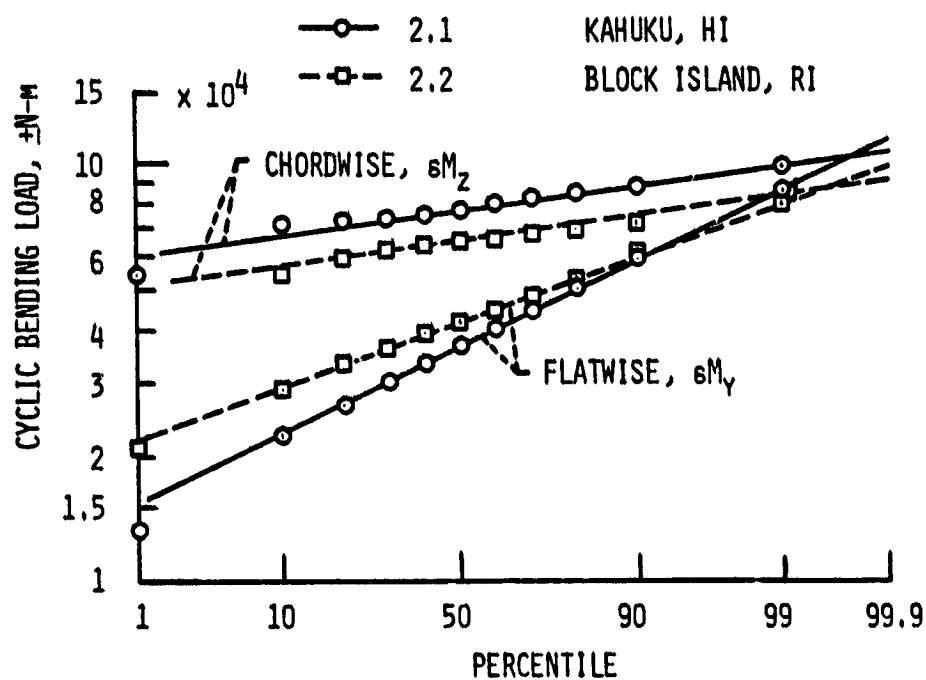


(b) System efficiency

Figure 6. -- Test series 4.1 power conversion performance compared with theoretical performance (Mod-1 steel blades at Boone, North Carolina).



(a) Mod-OA aluminum blades (at 5% span)

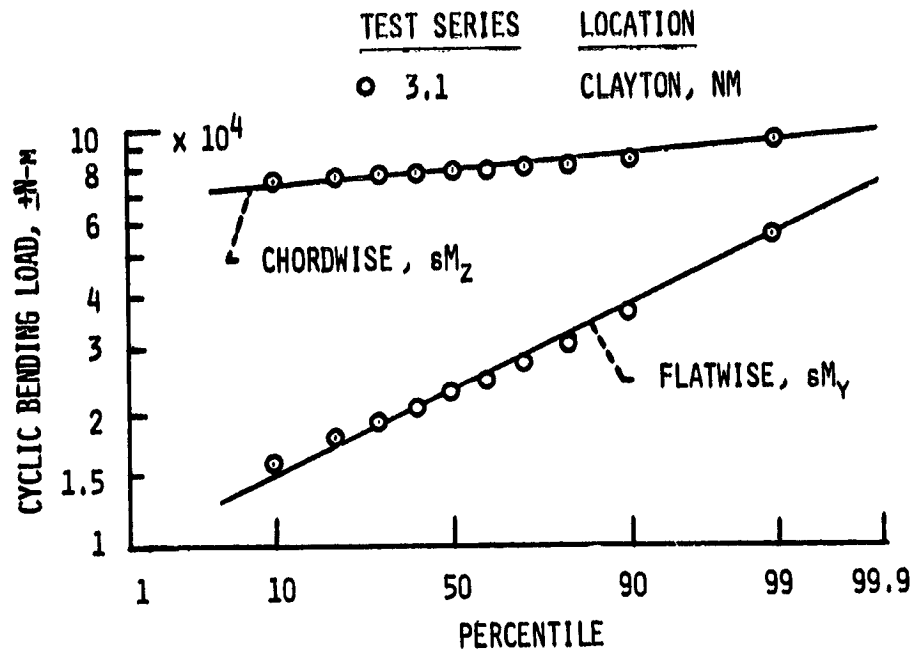


(b) Mod-OA wood blades (at 5% span)

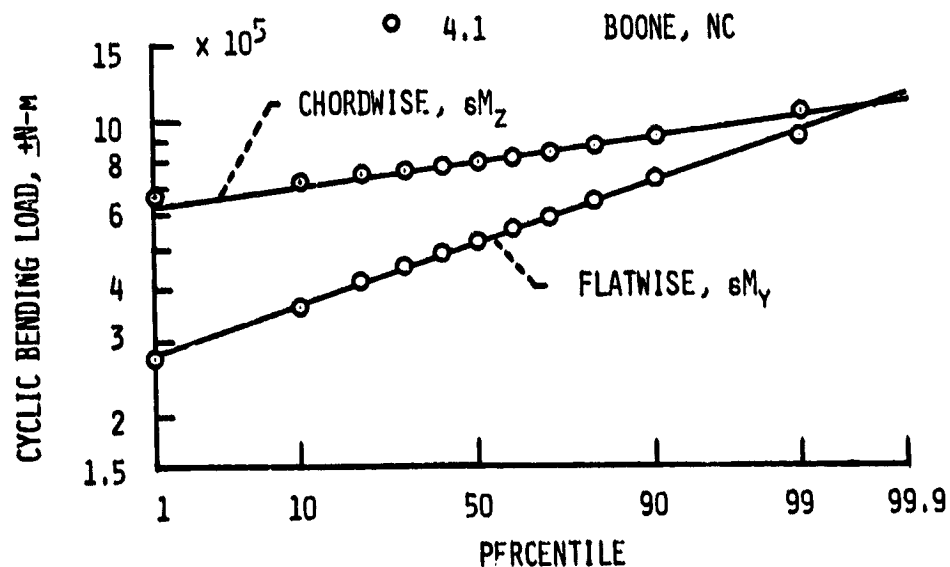
Figure 7. - Probability distributions of blade cyclic bending moments, with log-normal distribution curve-fits.



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(c) Mod-OA wood/fiberglass blades (at 7% span)



(d) Mod-1 steel blades (at 10% span)

Figure 7 (Concluded). - Probability distributions of blade cyclic bending moments, with log-normal curve-fits.

OPERATING EXPERIENCE WITH FOUR 200 KW MOD-OA  
WIND TURBINE GENERATORS

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The objective of the Mod-OA wind turbine project is to gain early experience in the operation of large wind turbines in a utility environment. Four of the 200 kW horizontal axis wind turbines, designed by the Lewis Research Center of the National Aeronautics and Space Administration, have been built and installed at utility sites. Since the first installation in 1977, the machines have accumulated 25,000 hours of operation, and generated 2,500 Mwh of energy. The Mod-OA wind turbines are a first generation design, and even though not cost effective the operating experience and performance characteristics have had a significant effect on the design of the second and third generation machines developed in the Federal wind energy program. The Mod-OA machines have been modified as a result of the operational experience, particularly the blades and control system. The latest machine installed operated nearly 6000 hours during the first year of operation, achieving an availability of 80%, and average plant factor of nearly 0.5, while producing 850 Mwh of energy.

This paper discusses the machine configuration and its advantages and disadvantages, particularly as it affects reliability. It also describes the machine performance, both availability and power output characteristics.

INTRODUCTION

Wind energy systems have been used for centuries as a source of energy for man. The applications have ranged from pumping water and grinding grain to generating electricity. These machines have generally been small, but at times considerable interest, both in the United States and Europe, has existed in developing large wind driven generators. However, interest in these systems has declined because they were not cost competitive with the fossil fuel systems of that era.

The recent changes in the energy situation have made it necessary to develop alternative energy sources. Wind energy is one of the most highly developed forms of solar energy, and may be a viable alternative energy source.

The Federal Wind Energy Program was established to enable research and development on the many applications and concepts of wind energy systems. This program originated at the National Science Foundation and is currently directed and funded by the Department of Energy. This program is designed to provide the continuity and sustained research and development effort generally lacking from the previous privately funded ventures.

One phase of the program is to develop the technology necessary for the successful design, fabrication, and operation of large, horizontal axis wind turbine systems. This phase of the program is managed by the Lewis Research Center of the National Aeronautics and Space Administration. The Mod-OA machines are the first wind turbines placed in utility operation under this program. The objective of this project is to obtain early operation and performance data while gaining initial experience in the operation of large horizontal axis wind turbines in typical utility environments. These are the first wind turbines in 30 years to operate routinely on a utility grid. The key issues to be addressed through these operations include:

- o Compatibility with utility grid.
- o Demonstration of safe unattended operation.
- o Wind turbine reliability and maintainability.
- o Operations and maintenance support.
- o Public and utility reaction and acceptance.

The heart of the Mod-OA project is the field operations. Machines are installed in four utilities of greatly differing size, technical capability, climate, geographic location, topography, and wind resource. The operations, routine maintenance, and troubleshooting and repair are performed by the utility as completely as possible. This approach provides the best simulation of eventual commercial operations. Although these first generation machines are not being operated for the prime purpose of producing power and thereby demonstrating commercial usefulness of these machines, they are maintained in a normal utility manner when possible. The major exception to this maintenance procedure is that major failures result in lengthy shutdowns for analysis, redesign and modification. Thus the operations represent a mix between utility simulation and experimental operations.

This report documents 25,000 hours of Mod-OA operational experience. The characteristics of the wind energy generated, the machine performance, and the subsystem strengths and weaknesses are

discussed. The report also presents an assessment of the project success in fulfilling its goals and objectives.

The Mod-OA machine is based very heavily on the Mod-O design, so an understanding of the origins of Mod-O is necessary. In 1973, when it was decided to build a research wind turbine to be known as Mod-O, the size, power rating, and basic design were chosen rather arbitrarily. A literature search did not locate substantial technical design information. Several persons who had been involved in wind turbines before were contacted, and limited help was received, but they were generally unable or unwilling to provide much specific help. The Mod-O turbine was essentially a fresh start in an unknown technical field.

The machine was to be "large," but not so large that size became a major hindrance. It was not designed to be cost effective, but rather a build it strong enough to last philosophy was used. It was a laboratory type experiment, containing an extensive data system and operated by experienced personnel under controlled conditions and carefully monitored.

The decision to install wind turbines in the field came almost simultaneously with the initial operations of Mod-O. The design was to be upgraded slightly, therefore the name Mod-OA, and installed at field sites as soon as possible. Basically the power rating and, therefore, drive train strength, was increased, and automatic control and safety systems were added. The first Mod-OA installation was completed two years later, and the first large wind turbine to be installed on a utility grid in the U.S. since WW II began operations.

## CONFIGURATION

A cutaway view of the Mod-OA nacelle is shown in Fig. 1. The machine is a two blade downwind configuration, using laminated wood-epoxy blades. The hub houses the full span hydraulic pitch mechanism and spindle bearing, which support the blades in a fixed coned position. The low speed shaft, to which the rotor is attached, is supported by two rolling element bearings. The 3 stage parallel shaft gearbox has a hollow input shaft through which the electrical wiring and pitch actuator hydraulic supply line pass. The synchronous alternator is coupled to the gearbox through a v-belt drive, which allows rotor speed changes, and a fluid coupling which provides drivetrain softness and damping. A disc brake is incorporated, on the high speed shaft of the gearbox, for maintenance and emergency shutdown. The bedplate is a box beam structure, and the nacelle housing is fiberglass. The yaw drive is electric, and uses dual motors and gearing to provide sufficient torque. A disc brake provides yaw axis stiffness and damping. The tower is a stiff 4 leg truss design, bolted to the reinforced concrete slab foundation. The switchgear, microprocessor based control system, safety system, and data systems

are located in the control room located beneath the tower. A detailed description of the machine design is given in Ref. 1.

The Hawaiian machine is slightly different in that the v-belt drive to the generator is eliminated, and the yaw drive is hydraulic (Ref. 2, 3).

#### SITE DESCRIPTION

The machines, shown in Figure 2, are identified as Mod-OA1, 2, 3, and 4 corresponding to the order of installation. Mod-OA1 was installed in late 1977 in Clayton, New Mexico. The Clayton utility is municipally owned, and isolated from other systems. The power plant, primarily natural gas fueled, supplies from 1 to 3.5 Mw to the town of approximately 3000 people. The plant is located approximately 1/2 mile from the wind turbine, and personnel are available 24 hours a day to service the wind turbine.

The second installation is on the Island of Culebra, Puerto Rico, and was completed in mid 1978. The Island is located 20 miles off the coast of mainland Puerto Rico. Electric power is supplied from the mainland thru an underwater cable. The personnel supporting the wind turbine are primarily located in San Juan, and travel to the island by airplane as required. The utility response to wind turbine faults is thus basically limited to a single shift operation, and usually involves a one day delay.

The third installation was completed in mid 1979 on Block Island, Rhode Island, located 12 miles off the coast of Rhode Island. The privately owned utility, isolated from other electrical systems, serves the population of approximately 300 year around residents, and up to several thousand persons during weekends in the summer. The load varies from approximately 250 kW to over a megawatt. The power plant, located a few hundred feet from the wind turbine, usually operates a single diesel generator at a time. The power plant is attended 16 hours a day. Personnel are available to support the wind turbine for one shift, but can usually respond rapidly if needed.

The fourth machine is located at Kahuku, the north side of the Island of Oahu, Hawaii. This site is 45 miles from Honolulu, where the investor owned utility is based. Personnel assigned to the machine are available 16 hours a day, including weekends. The site is in an area currently being developed for a multimegawatt wind turbine farm.

The environmental conditions at these sites also vary radically. The Clayton, New Mexico site has temperatures from 00°F to 100°F. Icing conditions are common in the winter, but the site is very dry typically. The winds are above cutin two thirds of the time, and

exceed cutout 50 to 100 times a year. There are strong diurnal variations, with very smooth night winds.

The Culebra site is a coastal tropical trade wind situation. There are minimal temperature variations, and the wind is smooth, and rarely above 30 mph except during hurricanes. Wind direction is also nearly constant. Corrosion from the salt laden air is severe, as at Block Island and Hawaii.

The Block Island site has temperature variations slightly less extreme than Clayton, but higher humidity and rainfall. The average wind is slightly lower than Clayton, but much gustier, and is above cutout more often.

The only significant difference between the Hawaii and Culebra sites is the wind velocity. The wind at Hawaii is above cutin over 90% of the time, and above rated far more than at any other site.

#### UTILITY INTERACTIONS

One of the early concerns with wind energy was that the variable wind turbine output would not be compatible with the utility. Also, would there be any unusual constraints on the interconnection to the utility. A goal of the Mod-OA project was to resolve these issues.

The compatibility of wind energy with a utility has a significant effect on the value of each kilowatt hour (kWh) generated by the wind turbine. If the wind energy contribution has a negligible effect on the utility, as has been the typical case with Mod OA installations, the value, per kWh, is the greatest. However, if the utility has to adjust its dispatch strategies, spinning reserve requirements, and voltage or frequency control, the value of the wind energy decreases. Also to be considered are the possible increases in maintenance and decreased generation efficiency resulting from greater load swings or off-optimum operation of the generation equipment.

Although the addition of wind energy may require changes in power generation strategies and costs, they may be economic questions considerations and not effect power quality. What the utility supplies to the customer is a voltage, of well defined amplitude, waveshape, and frequency. And wind turbines, while generating power, do little to support, and may even hinder, the maintenance of voltage amplitude or frequency. All large wind turbines at this time use conventional generators and thus do support waveform control. But even waveform support may become a factor as advanced designs may incorporate inverters.

The Mod-OA installations have created no significant interface difficulties. In Hawaii and Puerto Rico, the penetration is less than .1%. The Island of Culebra, Puerto Rico, is small, but it is tied thru an undersea cable to the main island grid. In Clayton, New Mexico, the wind power penetration can reach 20%, but does not effect utility operations (Ref. 4). Increments of diesel power which could be added to or taken off line are still large compared to the wind power, and in fact, if a single diesel is used, its overload capabilities are sufficient to sustain the grid if the wind turbine output would be lost. And maintenance levels and efficiencies have not apparently been changed by the introduction of wind power, nor has the quality of the power supplied by the utility decreased.

The wind energy penetration at Block Island, however, is very high and the interface has been a problem. During the winter, the penetration levels exceed 50%, and have averaged 15% over a month. At this site, the generation equipment in operation has been varied due to the wind turbine, and the effects have been significant enough that the fuel efficiency of the diesels does decrease, the maintenance increases, and the power quality delivered decreases. These are effects on a small utility with a single machine and massive penetration, and do not directly predict the effect of several large farms on a large utility. However, the interface requirements for some of the planned and proposed systems will not be insignificant as has generally been the case in the Mod-OA program. The economics of wind energy assume that like base generation, wind energy will be used whenever it is available. But unlike base generation, the output is highly variable and unpredictable. Each new generation technology, whether hydro, diesel, steam turbine, gas turbine, or nuclear, required new operational strategies, but perhaps none were as "different" as wind. The following section shows the output characteristics of the Mod-OA wind turbine to help define the interface requirements.

The interconnection to the utility grid uses a transformer to convert the 480 volt generator output and auxiliary load buses to the utility grid voltage, 2.4 to 12 Kv in these installations. A reclosure for isolation and grid fault protection is connected between the transformer and the utility grid. This interconnection does not require any abnormal line stiffness, and is typically made on an existing feeder circuit.

Mod-OA wind turbines operate in a VAR support mode, and as a power source as available from the wind. Thus the output is best characterized by the output current or power, both the real and reactive components. The actual effect on a utility is then determined from the utility system impedance and voltage and frequency control gains and response rates.

Output voltage, that is excitation control, on the Mod-OA is a fast, inner loop on voltage and an outer loop on VARS, typically

controlling for 90 KVAR leading. This mode was chosen to provide generator overexcitation to prevent slipping out of synchronism. VAR generation provides power factor correction for the utility and is, therefore, generally advantageous. In practice, staying in synchronism has never been a problem, so VAR level could be set based only on utility needs. Output voltage fluctuations have not been a problem on these machines, and has never been measured with transducers having enough resolution and response rate to show any voltage fluctuation. Additionally, other wind turbines have operated in constant voltage, constant power factor modes, and with induction generators without causing unacceptable voltage fluctuations.

Power output fluctuations, besides causing possible voltage fluctuations, require other generators to change power level to compensate and maintain frequency control. The power fluctuations resulting from wind generators are so unlike the normal generation that wind generation is often treated as a (negative) load. The power output traces shown herein are for OA wind turbines at various sites, but are generally applicable to all turbines. The absolute amplitudes would of course be different. The frequency content would also change.

The results shown illustrate typical behavior over several time spans. At one extreme, power variations with a frequency content of several hertz can be seen. The other extreme shows data based on weekly averages.

There are four separate identifiable components to a Mod-OA wind turbine power spectra. In general, these apply to all wind turbines, but the characteristics certainly vary. The four components are: a power impulse caused by blade passage behind the tower, the characteristic introduced when the machine is above the rated wind speed and controlling blade pitch to regulate the power output, the power variation in direct response to wind variations when operating below rated wind, and the start/stop transient as the wind traverses the cutin/cutout criteria. These components are listed in the order of decreasing frequency content, and generally in the order of decreasing interest and concern.

The shortest time spectra plot shown in Figure 3A illustrates the blade passage phenomena, the so-called 2P or two per rev for a two-bladed rotor. The impulse is a 10-50kW p-p variation depending on power level and wind shear. The prime cause of the 2P in these machines is the tower shadow effect on the downwind rotor. Changes in tower design, teetering, greater damping, more blades, and upwind configuration will effect the amount of this component. The amplitude and frequency appears somewhat random in this figure, and unsymmetrical between blades, due primarily to the machine resonances and wind gusting. The 2P variations are more pronounced in Figure 3B. The 2P variations are important to the machine designers because they are a source of cyclic stress and may be the design drivers for



damping and peak torque criteria. To the utility, it may represent a source of voltage fluctuation, but is too fast to cause any effect on frequency control. In the Clayton operation, it tends to act as a "dither" signal for the diesel governors, and actually improve the frequency control by reducing the deadband. The 2P effects would be integrated out in a farm situation where the machine rotors would typically be out of phase with each other.

The second component of power fluctuation is illustrated in Figure 3B, where the wind turbine is controlling pitch to regulate power. The 2P is very obvious in this figure, but the component of interest is the power variation about the 200kW setpoint in response to the wind and pitch angle changes. The controller action is a proportional and integral control based on the power signal. The mean power level, based on a per revolution average, varies about  $\pm 25$  kW about the 200 kW setpoint. Clipping caused by the recorder is limiting the peak signal to 230 kW in this figure. Actual peak power is approximately 250 kW worst case. The gusting during this data case was rather severe, approaching 5 mph/sec. A longer term case is shown in Figure 3C. The mean power is very constant, the variations are due to the 2P, and wind gusting and controller response.

The peak powers and fluctuations under these conditions generally size the strength of the drive train components, and are thus critical to the machine designers. It also is of great interest to the utilities, but possibly because it is definable and controllable and thus more easily meaningful to discuss than the next case shown. However, the frequency components generated at above rated power should integrate out in a farm, if they don't cause interaction between the machines.

The most common wind turbine operating mode is below rated power. And present designs are tending toward higher rated powers per swept area, thus raising the rated wind speed. Figure 3D is a 6 hour power trace in smooth winds with the 1P and greater frequency components removed. During this period, the machine ran continuously with the output ranging from nearly 200kW to slightly below zero. (The cutoff criteria is -10kW average.) Other typical cases are shown in Figures 3 E, F, G, H. Figure 3E is the ideal but rare case where the machine runs continuously at rated power. Figure 3F is more typical with operation above rated part of the time and below rated part of the time. Figure 3G is steady below rated operation. These are night winds on the plains or trade winds. The final case is an extreme shown in Figure 3H. In 5 hours about a storm front, the machine shut off on low winds before and after the storm, and in high winds during the storm. This operation, although infrequent, and fully automatic, will not filter out significantly in a farm of wind turbines, and will require rapid dispatch adjustment.

The final component of the wind turbine output characteristics is the start/stop cycle. In low winds the transition is very smooth and

causes no perturbation in the utility operation, but the cycles may be frequent. Figure 4A contains 4 cycles in less than an hour. However, the Clayton machine typically averages 2 hours per cycle, and at other sites the machines have exceeded 100 hours continuously.

The high wind cycle, as shown in Figure 4B, is much more infrequent, 100 per year, but more severe. The power decreases and increases at approximately 25kW/sec.

#### MACHINE PERFORMANCE

The machine performance is basically a discussion of hours of operation or energy generation. Although the 25,000 hours of operation have produced extensive data, a meaningful analysis is complicated by the effects of the experimental nature of the program. This section discusses the actual and predicted performance of the machines, the major outages, and the trends and effects of ongoing modifications.

The simplest description of the performance is given in Fig. 5. This curve shows the performance in a steady state mode, that is it does not contain any information about start-up/shut-down times, hysteresis about the cutin/cutout wind speed, or the responses to gusts. The curve also ignores temperature effects, yaw error, and wind shear variations for example, and implies 100% machine availability. All these factors must be accounted for in determining annual energy production. However, the curve of Fig. 5 can be, and has been, verified with a relatively small, several hour, data sample.

Verification of the actual versus predicted machine energy is far more difficult. Thus the measure of machine performance is not stated as an energy capture percentage based on annual energy available, which would be all encompassing, but on the components parts. The major components are the aerodynamic efficiency, drive train efficiency, machine availability, yaw pointing accuracy, start/stop losses and cutin/cutout setpoints or parameters. And these components are interactive. For example, reducing the cutin wind speed tends to increase the startup time. Energy generation would increase, as would sync time, but average power would decrease. And the likelihood of not starting satisfactorily increases, resulting in decreased availability. Thus, although reducing the cutin wind speed helps energy capture, it is very difficult to quantify the improvement. Meanwhile other easily measureable and understandable performance parameters deteriorate. Except to those closely connected with the program, many of the control system improvements made on these machines, for example, do not appear to have had as much effect as has actually occurred due to offsetting effects of changes like cutin/cutout criteria.

One measure of the machine performance as an energy source is shown in Fig. 6. The energy production of the four machines is plotted versus calendar time. The steepest slope portions of the lines represent excellent machine performance (primarily availability) and good winds. The horizontal sections represent prolonged outages.

These outputs represent average plant factors (output compared to wind turbine rating) of 0.1 to 0.15 for Clayton, Culebra and Block Island, and .5 for Hawaii. Deleting the periods of complete machine outage due to blade replacement at the sites (none at Hawaii) and the part time operations at Block Island, would put the average plant factor in the .2 to .3 range for the first three machines. Part time operations at Block Island were required due to potential TV interference before a cable TV installation was completed. Thus for the first four months the machine was only operated 40 hours per week. Although the theoretical energy capture at these sites has not been computed for the entire period, spot checks have shown a good correlation if availability, start/stop losses, and yaw error and other minor effects are taken into account. Availability is the major factor.

The availability of the Clayton machine is shown in Fig. 7A. Several trends do exist in the data. First, the long term average availability has not changed much since initial operations. However, the shorter term averages, 1-2 months, have improved. During the first year there were many failures, both major and minor. Both the utility and NASA responded rapidly to failures, but neither had the experience to make rapid repairs. Thus there were no excellent (high 90's) periods, but also no long total shutdowns. As the program emphasis changed, failure response became slower, and more analysis was done before operations resumed. However, the utility's capabilities were greatly improved, so more repairs were done using local crews, and less lost time. Also, machine improvements were being made so there were fewer major or minor failures, except for blades. As a result, there are many more excellent weeks, and fewer mediocre periods. However, the total outages, although no more frequent, lasted far longer. A graphic demonstration is shown in Fig. 8, where the weekly availability, neglecting the weeks of total outage, has risen substantially, and the "typical good" week has risen from the low 80's to the high 90's.

The availability improvements, Fig. 7B,C, are more dramatic for Culebra and Block Island. Both sites have had one major shutdown for blade replacement or repair, but there is also a marked rise in typical week availability. Neither site has utility personnel available 24 hours a day, and therefore minor problems cause significant outages. The availability improvement primarily reflects the decrease in "glitches" due to control system improvements. There have been very few major failures at either of these sites. The Clayton operation is indicative of operations with a local repair

crew, on 24 hour call, which might simulate farm operation. In contrast, the Culebra situation is a remote, inaccessible installation which must run in an unmanned fully self-sufficient mode.

The Hawaiian machine availability, Fig. 7D, has remained quite high throughout its life, and averaged 0.8 for its first year of operation. Wind power has a high priority in that region, and the combination of high utility capability and support at all levels and the machine improvements developed from the experience at the other sites has made this machine very successful.

At all sites, the utility must be given much of the credit for the high availabilities. The personnel working on the machines are typically diesel mechanics, yet they perform sophisticated repairs and troubleshooting on complicated systems. Their enthusiasm and personal commitment to this experiment has been a key element in its success.

#### Component Experiences

A detailed discussion of the failures and resulting modifications is outside the scope of this report. However, this section covers the general areas that have been significant in the operations.

The blades have been the greatest single problem in this program. The original aluminum blades were not expected to be 30 year life low cost components. But the actual life, generally about 1000 hour/per repair, was much less than expected. The basic cause was a design deficiency in one area. After an iteration of repairs, the modifications developed were very successful when applied to an undamaged blade. The Culebra wind turbine operated over 4000 hours without repair. The greatest improvement, however, is the result of the low cost blade program, resulting in the wood epoxy blades operating essentially faultlessly at 3 sites with over 10,000 hours cumulative running, and the fibreglass blades to be tested at Clayton.

The rotor hub has required repairs, but always in parallel with blade repairs, and thus has not affected the availability. Due to the high loads encountered in a rigid hub, the pitch axis bearing design is difficult. The early designs did not maintain preload, and the pitch control gears wore rapidly. These problems have apparently been solved through minor redesign and upgraded lubrication requirements. No further hub modifications are anticipated, although the current lubrication requirements are undesireably high.

The drivetrain has been essentially troublefree except at a single site. The original alternator design was not sufficient for the belt drive configuration employed. This led to a bearing failure at Clayton, and redesign of the alternator drive-end bearing. However, the alternator shaft was damaged by the bearing failure, eventually

requiring replacement of the alternator. The bearing was replaced before failure at the other sites, and the 4th machine is a direct drive configuration eliminating the problem. Also, the fluid coupling has failed repeatedly at Clayton. These failures were probably accelerated by the alternator failure, but it was not the sole cause. The fluid coupling is not mounted according to the manufacturer's specifications, and as a result goes thru resonance every startup. A strengthened case replacement is now operating in Clayton and may solve the problem. There have been no significant mechanical drivetrain failures at other sites.

The only other mechanical system problem has been the yaw drive. Yaw axis loads are high in a rigid hub two blade machine, and the yaw system can impart high blade loads also. Actual hardware problems in the yaw system have been rare, but the loads are always a concern and several minor modifications have been made to reduce the load levels.

Hydraulic and pneumatic systems are used for pitch control, yaw system damping, and the rotor brake. These systems have been serious problems in that although malfunctions are not frequent, they are not easily repaired. Most problems have been from shifts in component settings, but pump failures, actuator and valve leaks and rotary coupling failures have occurred repeatedly. An upgrading of these systems is reducing the failure rates, but further improvement is necessary.

The control system, including switchgear, safety system, and remote control, has consistently caused the greatest number of shutdowns, but has not resulted in many major outages. Most shutdowns are not the result of hardware failures, and a system reset is all that is required to resume operations. However, at remote sites several hours to a couple days time is often lost. Control system development has proceeded on several fronts and has been the most heavily modified portion of the wind turbine, except blades. These changes have been to: Reduce blade loads, particularly during startup and shutdown; increase energy capture especially through low wind start/stop criteria; decrease the number of false shutdowns; improve the machine protection; provide better more reliable remote control; and ease trouble shooting of the control system. The approach is to perform more tasks with the microprocessor, delete the separate discreet systems used in the original design, and to use improved algorithms to obtain better control.

Extensive development has also been done on the start up procedure. Many energy prediction codes assume no time loss in start up. And although the energy in the start up winds is quite low, the percent of operating time involved can be quite high. During the first year of operations at Clayton, the machine spent approximately 10% of its operating time in start up. The machine would start at 12 mph, and each start took typically 4 minutes. And only 60% of the starts were

successful. The other 40% would shutdown and restart automatically without operator action, but the restart would proceed more slowly, and take 6-10 minutes typically.

The start up is now done at 10 mph, less than 60% of the wind energy available at 12 mph, and takes 2 minutes typically. Approximately 10% of the start attempts are unsuccessful, but the restarts are fully automatic and as fast as the normal start up.

The total loss due to start up time is difficult to assess because the winds are so low. Assuming 100 starts per week, 2 minutes per start, and 25 kW average would be made during the lost time, the loss is about 1% at a 12 mph site. The loss would be less at a higher or steadier wind site.

The two and a half years experience and the modifications made during that time have had a marked effect on the system reliability. The MTBF, mean time between failure, was in the order of 200 hours during the first 6 months at Clayton. The comparable period for Hawaii has a MTBF three times as high. The MTBF is based on operating hours, and only counts failures requiring hardware replacement. A more dramatic increase has been in a mean time between incident calculation, where any situation requiring an operator action is recorded, even though such an action may just be pushing a button at the dispatch office. The interval has gone from a few hours initially, with most actions requiring a site visit, to typically 50-100 hours. A major reason that the Clayton availability has not increased as dramatically as at the Culebra-Block Island facilities is that the Clayton utility has always been able to respond rapidly at any time. The other sites, being remote or without 24 hours dispatcher monitoring, are affected much more by minor incidents.

During the next couple years, it is expected that the machines will continue to perform better, and weekly availabilities will typically be above 90%. And due to the blade improvements, major outages are not expected. However, we expect the utility response to decrease as the turbines are no longer the new "engine" in the system. Thus minor failures will have an increasing effect on availability. The infant failures and major design deficiencies are now eliminated, but some middle-age wearout can soon be expected. Overall, the performance is expected to improve, but not markedly, and the maintenance requirements will become more routine.

#### PROJECT ASSESSMENT

The objective of the Mod-OA project was to gain early operating experience with large wind turbines. The 3 1/2 years and 25,000 hours of operation have fulfilled that objective, have been invaluable to the design of 2nd and 3rd generation machine designs, and the public and utility perception of wind power. Also, the

machines themselves, even though 1st generation, are considered very successful. These machines are being watched very closely by utility and alternate energy groups as the best indicator of practical wind energy generation.

There were also specific goals for the project. One goal was to demonstrate unattended failsafe operation. The machines are running unattended, and the protective systems have successfully detected failures before the failures resulted in other serious damage. The unattended operation has had a significant effect on reliability, pointing out the need for very reliable control and fault detection. Two other related goals were investigating the reliability of wind turbine systems and the required maintenance. The wind turbine reliability was initially below the levels required for commercially viable systems, but problem areas and systems have been identified, and generally corrected and the systems changed in 2nd generation designs. However, the high failure rate has provided an accelerated test of the maintenance requirements, particularly the skills and special tooling and crane requirements. Although most field diagnostics are provided by LeRC engineers, most of the troubleshooting and repair is accomplished by the utility, generally by regular diesel mechanics and electricians. Most of the diagnosis could also be performed by the utility if better manuals and troubleshooting guides were available.

A fourth goal was to assess the compatibility with the utility grid. The grid interaction with these machines has been negligible except at Block Island, where the impact has been a very strong function of the utility diesel state of tune. The utility impact characteristics with Mod-0A machines have shown that the interface is not as severe a problem as was expected, and is in general very benign.

The final goal was to assess the public reaction, and may be the most critical issue. And the public should be divided into four groups: (1) the general public as visitors; (2) the residents of the local area; (3) utility personnel from other utilities and (4) the local utility personnel. The first group is the largest. It is estimated that 20,000 people have stopped to look at the Clayton wind turbine. Most visitors have a positive reaction, it looks good, wind energy is a good idea to pursue. Local residents are no longer in awe of the machines, and tend to be proud of having the machine, but pessimistic about its success. This is primarily a communication problem in that they are unaware of how much the machines have run. The pessimism largely disappears when given a few facts. Visiting utility personnel typically are aware of the economics involved, and view the Mod-0A machines as an experiment which can be very useful, but realize that the machine is not currently viable and that improvement is necessary. Their view of the project is very close to the programs intent. The utility personnel involved with the machine are nearly universally enthusiastic, strong supporters of the machines.

## CONCLUDING REMARKS

The Mod-OA project was developed to provide early experience in wind power operation in a utility. To date, the machines have operated 25,000 hours, and produced over 2.5 million kilowatt hours, exceeding the production of any other large wind turbines in the country. The machines have provided extensive data to verify the design codes and loads analysis tools, and to characterize wind turbine performance. Although these 1st generation experimental machines are not currently economical power producers, they have been valuable in assisting the technology development in later machines and in assessing public reaction and utility compatibility. The machines have evolved until they are currently reliable energy sources compatible with the utility requirements and capabilities.

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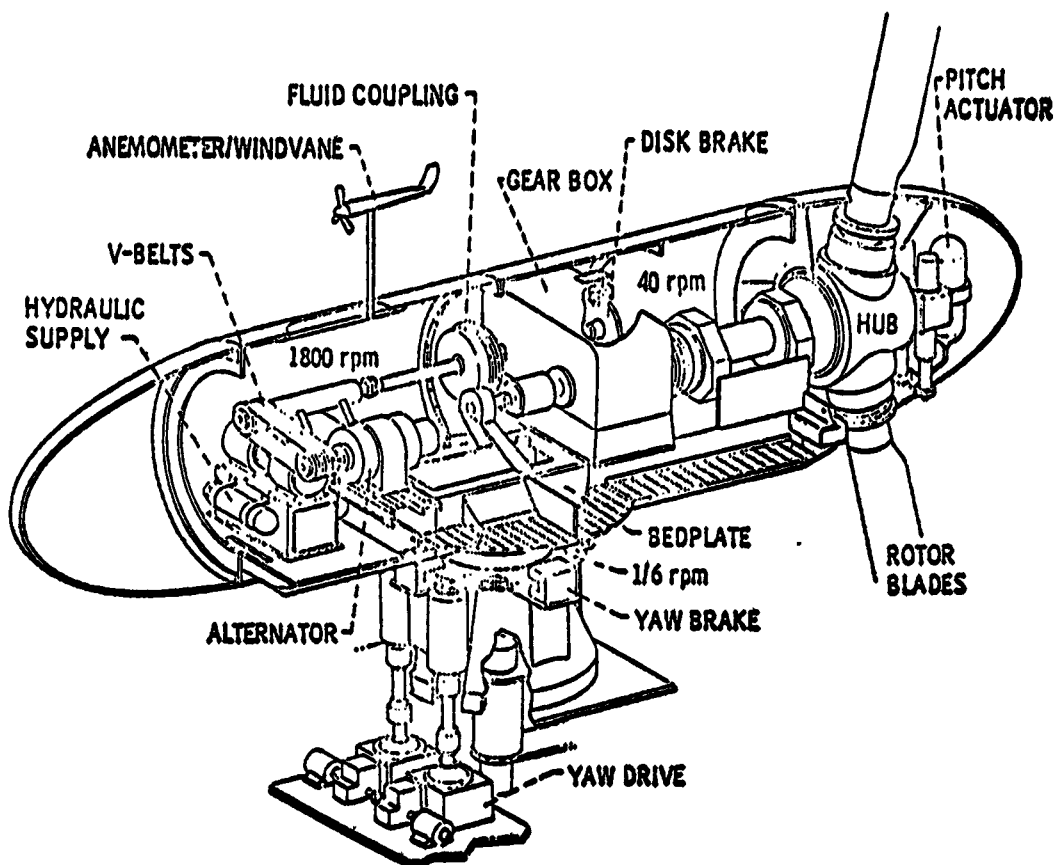


Figure 1. MOD-OA 200 kW Wind Turbine  
Schematic of Nacelle Interior

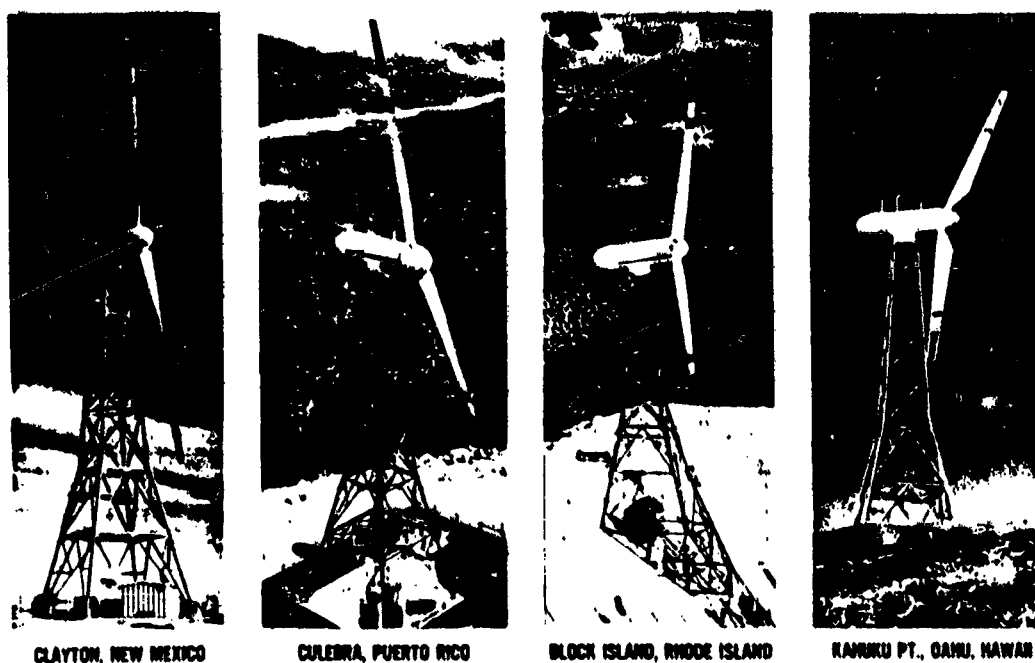


Figure 2. MOD-OA Wind Turbines

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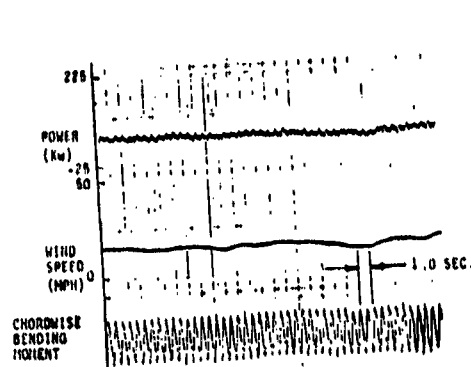


FIG. 3A

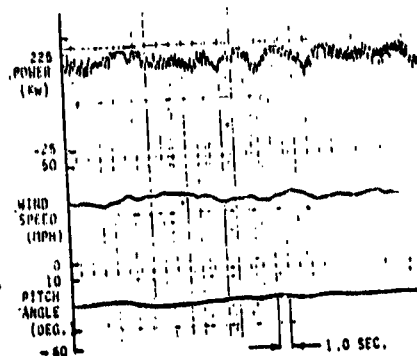


FIG. 3B

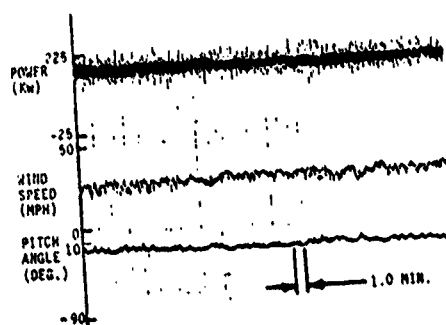


FIG. 3C

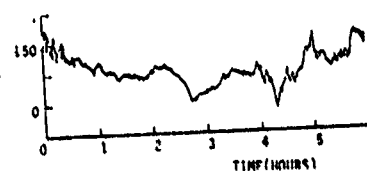


FIG. 3D

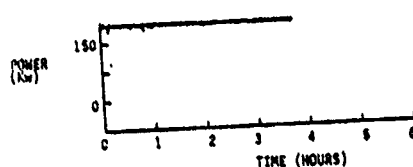


FIG. 3E

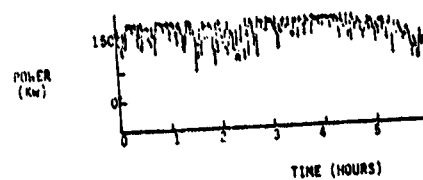


FIG. 3F

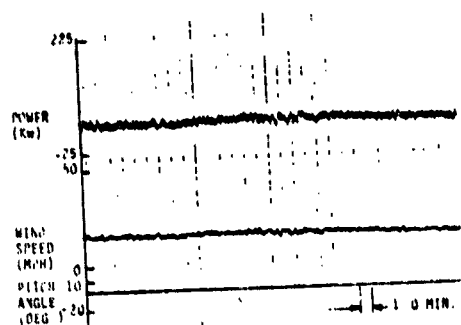


FIG. 3G



FIG. 3H

Figure 3. Output Power Variations

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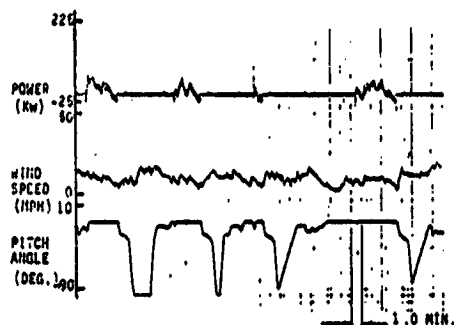


Figure 4A. Low Wind Start - Stop Cycles



Figure 4B. High Wind Start - Stop Cycles

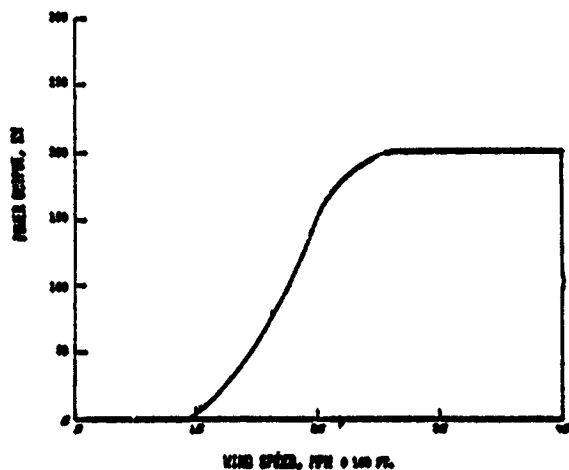


Figure 5. Power Output vs. Wind Speed

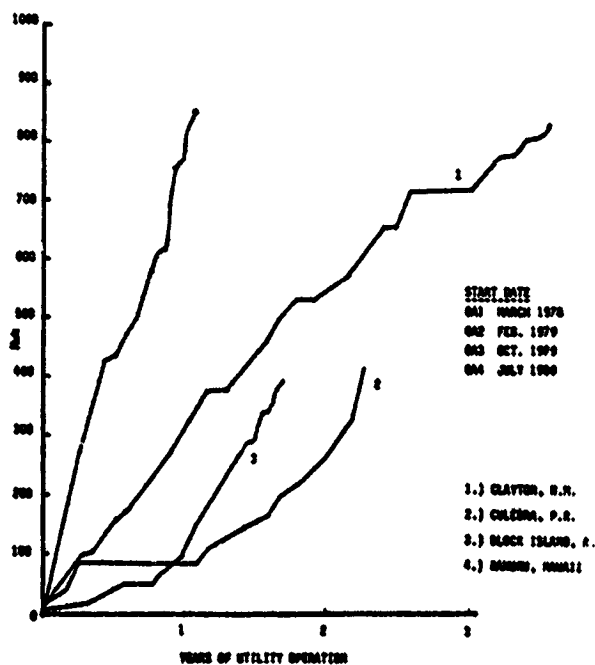


Figure 6. MOD-OA Wind Turbine Energy Production

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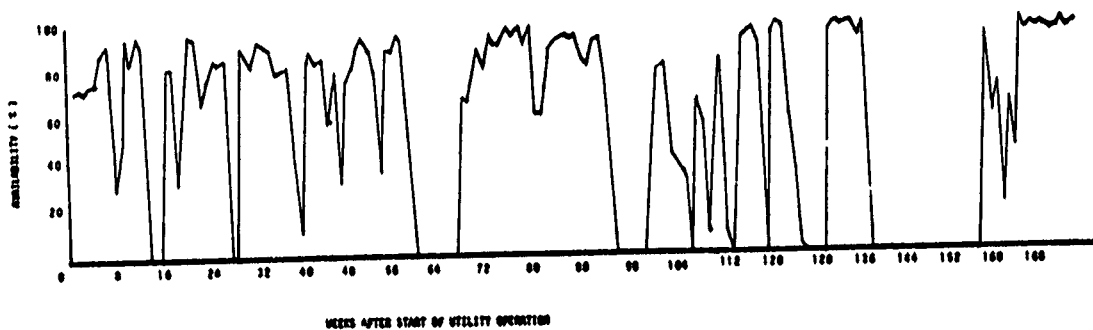


FIG. 7A - CLAYTON WIND TURBINE AVAILABILITY

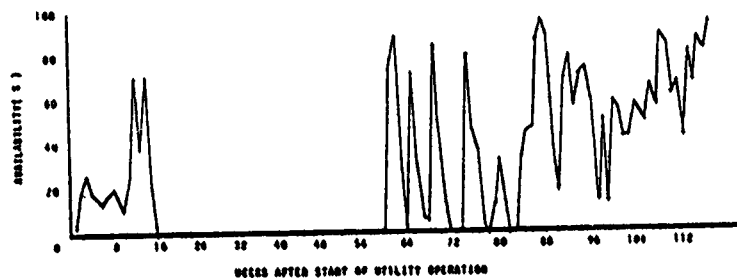


FIG. 7B - CULEBRA WIND TURBINE AVAILABILITY

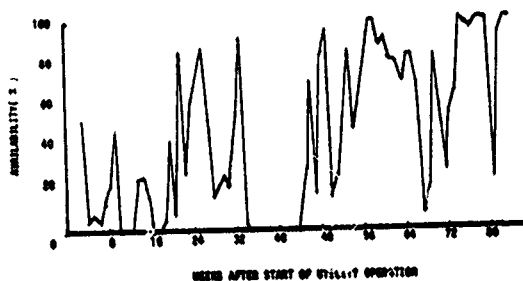


FIG. 7C - BLOCK ISLAND WIND TURBINE AVAILABILITY

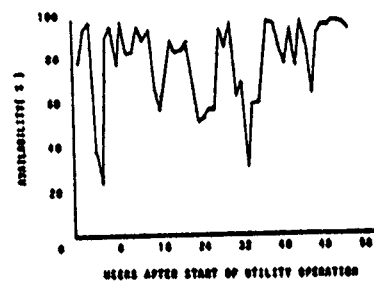


FIG. 7D - HAWAII WIND TURBINE AVAILABILITY

Figure 7. MOD -OA Wind Turbine Availability

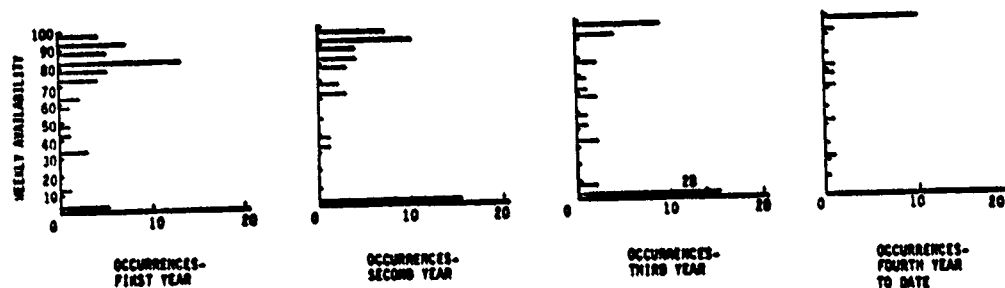


Figure 8. Clayton Wind Turbine Availability

## QUESTIONS AND ANSWERS

A. G. Birchenough

From: R. Hughes

Q: Have any tests been performed to determine the extent of radio-frequency interference created by different blade types?

A: *There have been no comparative tests on the machines. Small scale testing and analysis has been done by the University of Michigan.*

From: J. S. Wood, Jr.

Q: What percentage of energy is lost between the hub energy and electric output at the generator? Is the design of gearbox gears a factor? Has lube media been explored?

A: *The efficiency of the machine is about 90% at full power. The gearbox efficiency is 95% and is certainly a function of design. For example, the efficiencies of the planetary gearboxes for the larger machines are 98%. Lube media has not been extensively explored.*

From: J. Cirka

Q: What is your prediction that the major components of wind turbines (rotor, gear box) will achieve a 25-30 year equipment life? If insufficient data exists, what would be the earliest date that this equipment life goal could be verified?

A: *The major components were conservatively designed for a 30 year life and have not shown any abnormal wear to date. Life expectancies have not been updated for the actual loads experienced. The OA machines will probably not be operated for a long enough period to verify life predictions, but it may become available from the Mod-2 project experience.*

From: R. C. Henson

Q: What have maintenance costs been?

A: *The actual maintenance costs of the machines are not known. They are being operated as an experiment and are often modified. The experience to date indicates normal maintenance requirements of \$5,000-10,000 per year, not counting failures.*

From: L. P. Rowley

Q: Is there much yaw activity during the long periods of Mod-OA running? Does this adversely affect energy capture?

A: *The turbines spend 1-2 hours per week yawing and maintain the average yaw error at 5-10°. The energy capture loss for this yaw error is*

A. G. Birchenough (continued)

*a small percentage and the energy required to yaw is negligible. We restrain yaw activity and accept the energy loss because the yaw cycle is a high load situation on the rigid hub, 2-blade machine.*

From: T. Zajac

Q: Has any machine experienced a lightning strike? If so, any distress?

A: *We do not know of a lightning strike on a OA machine. The Mod-0 machine has been struck, resulting in instrumentation failures.*

From: C. Rybak

Q: Were the failures in the control system mainly hardware or software related?

A: *Early failures were hardware related. As the capabilities of the computer were expanded, a greater percentage were due to software errors. At present, the software is well debugged and the primary failures are in the hardware, although these failures are infrequent.*

From: R. Barton

Q: The "linear" yaw drive on Oahu was said to have less reliability than a geared drive. Is this mainly the result of the implementation with 8 actuators and associated plumbing rather than the concept?

A: *The 8 actuators have performed faultlessly. The reliability problem has been due to general hydraulic supply failures.*

From: R. Moment

Q: What design/material changes are indicated from your Hawaii and Culeban, Puerto Rico, experiences with salt atmospheres?

A: *The salt environment has caused one design change; the control room is air conditioned to eliminate fungus growth in the electronics. Components within the nacelle show very little effect. The tower itself and any other components exposed to the weather need to be protected.*

From: C. Tan

Q: Based on your experience at the 4 machines, what do you envision are the required annual operating and maintenance requirements of a MOD-OA system, estimated scheduled shut down time required per year, required number of blade replacements over the life of the machine?

A: *We do not feel the present MOD-OA system is a practical power production machine due to its high maintenance requirements. Normal scheduled maintenance is around 100 man hours a year (time on site),*

A. G. Birchenough (continued)

*and required minor repairs have also been of about this magnitude. We cannot estimate the requirements for major failure repairs. Based on our recent experience, i.e. wood blades and elimination of initial design faults, blades and major components would not be replaced during the life (30 years) of the machine.*

From: A. Jagtiani

Q: Can you tell me whether this machine will have the same audible noise and TV interference problems like those experienced with Mod-1 if installed near populated areas?

A: *The Mod-0A machines have lower noise generation and cause less TV interference than the Mod-1 due to design differences. However, noise and TV interference is a normal characteristic which must be considered in the siting. Two of the Mod-0A machines are located quite close to residences and have caused very little disturbance.*

EXPERIENCE AND ASSESSMENT OF THE DOE/NASA MOD-1  
2000 KW WIND TURBINE GENERATOR  
AT BOONE, NORTH CAROLINA

John L. Collins, Richard K. Shaltens  
National Aeronautics and Space Administration  
Lewis Research Center

Richard H. Poor, Robert S. Barton  
General Electric Company  
Valley Forge Space Center

ABSTRACT

The broad objectives of the Mod-1 Program are defined including the background information leading to the inception of the Program. Activities on the Mod-1 Program began in 1974 with turbine dedication occurring in July 1979. Rated power generation was accomplished in February 1980. A description of the Mod-1 WT is included. In addition to the steel blade operated on the WT, a composite blade was designed and manufactured. During the early phase of the manufacturing cycle a Mod-1A configuration was designed that identified concepts such as partial span control, a soft tower and upwind teetered rotors that have been incorporated in second and third generation industry designs.

The Mod-1 electrical system performed as designed with voltage flicker characteristics within acceptable utility limits. Power output versus wind speed has equaled or exceeded design predictions. The WT control system was operated successfully at the site and remotely from the BREMC dispatcher's office in Lenoir, North Carolina. During WT operations, TV interference was experienced by the local residents. As a consequence, WT operations were restricted. Although not implemented, two potential solutions were identified. In addition to TV interference, a few local residents complained about objectional sound particularly the "thump" as the blade passed behind the tower. To eliminate the residents' objections, the sound generation level was reduced by 10 db by reducing the rotor speed from 35 rpm to 23 rpm. During January 1981, bolts in the drive train fractured. A solution has been identified but not implemented as yet. During the past two years the public reaction has been overwhelmingly favorable toward the Mod-1 WT Program. This includes the vast majority of local Boone residents.



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### 1.0 OBJECTIVE

The overall objective of the 2,000 kW Mod-1 Project was to obtain early operational and performance data that could be used in the design of second generation cost-competitive wind turbines. The Mod-1 Wind Turbine was the first megawatt sized machine in the Federal Wind Energy Program to produce electrical power from wind energy. Specific project objectives were as follows:

- o Operational and performance data for a Megawatt sized wind turbine in a utility operated application
- o Demonstration of unattended, fail-safe operation
- o Involvement of utility as user and operator
- o Identification of maintenance requirements for large wind turbines

- o Involvement of industry in the design, fabrication and installation of a the wind turbine
- o Identify components/subsystem modifications to reduce cost, improve reliability and increase performance
- o Assess public reaction/acceptance of large wind turbines
- o Demonstrate compatibility with utility requirements

A very significant benefit of the Mod-1 Project was the discovery under some conditions that the wind turbine emitted an objectionable sound level to 10 families in the vicinity of the site. Methods to characterize the sound in order to establish acceptable sound standards and to reduce the sound levels became a significant part of the Mod-1 Program.

## 2.0 BACKGROUND

The Federal Wind Energy Program administered by the Department of Energy (DOE) has as one of its goals the development of the technology for practical cost-competitive wind turbines that can be used to supply significant amounts of electrical energy. As a part of the wind turbine development, the Lewis Research Center (LeRC) of the National Aeronautics and Space Administration (NASA) had the responsibility to carry out the Mod-1 Program. The General Electric Company (GE) under contract to LeRC, designed, built, and installed the Mod-1 Wind Turbine at Howard's Knob (Boone), North Carolina. Blue Ridge Electric Membership Corporation (BREMC), a rural cooperative with headquarters in Lenoir, North Carolina, received the power generated by the Mod-1 Wind Turbine; and BREMC operated the wind turbine remotely from the dispatcher's office in Lenoir.

## 3.0 CHRONOLOGY

Major project events are shown in the chronology listed below.

Project Initiated . . . . .	1974
Contract placed with General Electric Co. . . . .	July 1976
First Rotation Accomplished . . . . .	May 1979
Turbine Dedicated . . . . .	July 1979
Turbine Synchronized with BREMC Network . . . . .	September 1979
Began Semiregular Operation . . . . .	October 1979
Turbine Completed Acceptance Testing . . . . .	January 1980
Utility Training Completed . . . . .	February 1980
Machine Generated Full Power - 2,000 kW . . . . .	February 1980
Reduced Rotor RPM Modification Completed . . . . .	November 1980
Machine Developed Drive Train Problem . . . . .	January 1981

## 4.0 MACHINE DESCRIPTION

### 4.1 CURRENT MOD-1 WIND TURBINE GENERATOR

The Mod-1 2000-kW wind turbine generator is mounted on top of a truss tower with its horizontal rotor axis 140 feet high. Its two blades are 200 feet in diameter (fig. 4.1-1) and located downwind of the tower. The nacelle/bedplate, which supports and encloses all equipment mounted on top of the tower, is driven through a yaw-bearing assembly that rotates about the vertical axis of the tower in response to changes in the wind direction. The tower is 12 feet square at the top and 48 feet square at the bottom and is anchored to reinforced concrete footings at each leg. Figure 4.1-2 shows the machine installed on Howard's Knob, at Boone, North Carolina. The elevation at the site is approximately 4500 feet above sea level. The original design specifications are presented in table 4.1-1.

The wind turbine assembly consists of the rotor assembly, the drive-train/bedplate assembly, the yaw assembly, and the tower (fig. 4.1-3). The turbine rotor initially operated at 35 rpm and generated 2000 kW of electric power in a 25.5-mph wind (at 30 ft.), and was modified to 23 rpm and 1350 kW in November 1980. The hub and blades are connected to a low-speed shaft that drives a gearbox. In the gearbox the shaft speed is increased from 35 rpm to 1800 rpm and later 23 rpm to 1200 rpm. A high-speed shaft connects the gearbox to the alternator. The entire system weighs 655,000 lb, 335,000 lb machine weight and 320,000 lb tower weight. Table 4.1-2 presents a weight breakdown of the machine. The major components are described in the following subsections.

#### Rotor Assembly

The rotor assembly consists of three major subassemblies, the blades, the hub assembly, and the pitch-change mechanism. Each blade is attached to the hub through a three-row, cylindrical roller bearing that permits the full pitch of the blade from the power position (0°) to the feather position (90°). Blade pitch is controlled by hydraulic actuators operating through a mechanical linkage with sufficient capacity to feather the blades at an average rate of 8 degrees per second.

The blades are constructed of a monocoque, welded-steel leading-edge spar and an aerodynamically contoured, polyurethane foam afterbody with bonded 301 stainless-steel skins (fig. 4.1-4). Measuring 100.8 feet long with a tapered planform and thickness, the blade uses an NACA 44XX series airfoil with a thickness ratio varying from 20 percent at the tip to 33 percent at the root. The blades, which weigh approximately 21,500 lb each, are assembled in six main sections. Spar welds are located at five stations, as are the trailing-edge-section splices. A transition piece is welded to the spar to provide the blade continuity to the interface with the hub. A longitudinal stiffener and chordwise webs are welded in the spar to

provide buckling strength. Ballast weights are used at each blade tip for static and dynamic balance.

The hub assembly consists of a hub barrel and a hub tailshaft (fig. 4.1-5). The hub barrel houses the pitch-change bearing and supports the blades at a  $90^\circ$  cone angle. The tailshaft joins the barrel with a  $120^\circ$  saddle flange and a transition to the circular main-bearing seat and flange. The main rotor bearing is shrink fitted to the hub tailshaft and bolted to the bedplate adapter to form the rotor-bedplate interface.

The pitch-change mechanism positions the blades in response to commands from the control system. It consists of hydraulic actuators, swing links, a thrust ring and bearing, and two blade pitch rods (fig. 4.1-6). The stationary hydraulic actuators translate fore and aft motion to the rotating (35 rpm) pitch assembly through a thrust ring. This assembly is supported by both stationary and rotating swing link arms to maintain clearance from the low-speed shaft and thus allow the fore and aft motion to change the pitch of the blade through the pitch rods.

#### Drive Train/Bedplate Assembly

The drive-train assembly consists of a low-speed shaft and couplings, a three-stage gearbox, and a high-speed shaft that drives the alternator (fig. 4.1-7). The high-speed shaft incorporates a dry-disk slip clutch for protection against torque overloads and a disk brake that will stop the rotor in the event of an overspeed condition and also is used to hold the rotor in a parked position. The entire assembly is supported on a bedplate and enclosed in an aluminum nacelle fairing for protection.

#### Yaw Drive Assembly

Yaw rotation of the machine to align with the wind is provided by the yaw drive, which consists of upper and lower structures, a cross roller bearing, dual hydraulic drive motors, and six hydraulic brakes (fig. 4.1-8). Each yaw motor drives a pinion meshing with a ring gear on the inner race of the yaw bearing. The yaw brakes dampen dynamic excitations in yaw motions while the nacelle is being driven. These components are housed in a yaw structure that interfaces between the machine and the pintle structure of the tower.

#### Tower

The steel tubular truss tower (fig. 4.1-1) is made of seven vertical bays with the bracing designed for bolted field assembly. Tubular members were used to reduce "tower shadow" loads on the blades as they pass the tower. The tower was designed to provide stiffness in the lateral and torsional modes. The bending frequency is 2.8 times the rotor operating frequency, and the torsion frequency is 6.5 times the rotor operating frequency. The maximum design wind load is 150

mph. All the members of the tower were fabricated from A333 steel, which provides good low-temperature fracture toughness.

The tower is supported by separate foundations for each of its four legs. Because of the dead weight of the wind turbine, relatively small tension loads are developed in the foundation. Each leg is secured by eight 1.5-inch-diameter anchor bolts, hooked at a depth of 30 inches into the foundation. Tower baseplate shear loads react through a nonshrink grout to a lip on the foundation that is tied into reinforcing bars in the foundation.

### Control System

The control system for the WT includes a PDP Digital Equipment Corporation 11/34 computer located in the ground enclosure at the base of the tower. The PDP 11/34 interfaces with two PDP 11/04 micro-computers. One PDP 11/04 is located in the control enclosure, and the other in the nacelle. The control system provides unattended safe and reliable operation of the wind turbine plus features of a data logging system. It will automatically start, operate, and stop the machine, align it with the wind, and provide dispatcher control through a telephone link. In addition, if the control system detects any operation or machine anomaly, the control system is programmed to safely shut the machine down. Figure 4.1-9 presents a simplified control schematic. References 2 to 4 provide a detailed description and a summary of the design calculations, including an analysis of failure modes and effects.

### 4.2 KAMAN - COMPOSITE BLADES

Two composite rotor blades, designed and built specifically for operation on the Mod-1 wind turbine by Kaman Aerospace Corporation, Bloomfield, Connecticut, have recently been completed. These blades were developed as the second phase in NASA's on-going evaluation of the applicability of composite construction for very large wind turbine blades. The first phase served to develop the technology for such blades and demonstrated this in a 150 foot test blade, which was completed and static tested in 1978. This was the largest composite rotor blade ever constructed, and successfully demonstrated the potential of this material.

The final blades, illustrated in Figure 4.2-1, are fully compatible with the Mod-1 wind turbine and possess dynamic characteristics equivalent to those of the present steel blades. The blade's main structural member is the D-spar, which reacts all primary loads and comprises over 70% of blade weight. Construction of the spar utilized the Transverse Filament Tape (TFT) process, first used for a rotor blade in the 150 foot blade program. An epoxy resin is utilized for its superior fatigue strength, compatible with the 30 year design life of the blades. The afterbody portion of the blade, a lightweight structure which completes the airfoil cross section, is comprised of upper and lower panel members. These are of sandwich

construction, made up of inner and outer fiberglass skins with a honeycomb core of resin-impregnated kraft paper; the panels vary in thickness from 1 inch to 3 inches. An adapter fitting, of welded steel construction, is permanently installed at the inboard spar end, using a bolt attachment. The blades incorporate lightning protection, capable of withstanding 200,000 ampere strokes, and the lightning protection is configured to minimize the adverse effect on the inherently low TV interference characteristics of composites. The new blade also includes an ice detection device, as well as a polyurethane paint system and leading edge protection to withstand environmental effects.

#### 4.3 MOD-1A

Shortly after the completion of the Mod-1 Wind Turbine final design, a trade-off study was initiated on a conceptual design that would take advantage of innovative design approaches identified during the Mod-1 design experience, but could not be incorporated in the Mod-1 due to schedule and cost constraints. This design concept was identified as Mod-1A, and had as its basic objectives the reduction in weight from 327 to 200 tons and the cost of energy from 18 to 5¢/kW-hr (1978-\$), see Figure 4.3-1. In the trade-off study, three candidate systems were identified as shown in Figure 4.3-2.

Configuration 3 was selected which has as its major characteristics a teetered hub, two upwind blades with partial span control, an integral parallel shaft gearbox structure, an inclined rotor axis and a "soft" shell tower. The Mod-1A overall outline is shown in Figure 4.3-3. A view of the upper portion of the tower and nacelle is shown in Figure 4.3-4. Although the Mod-1A was not built, many of the concepts identified in this trade-off study have been incorporated in second and third generation designs.

#### 5.1 IMPACT OF POWER GENERATION OF UTILITY GRID

##### WT Power Generation System

The Mod-1 Wind Turbine (WT) power generation system is shown in Figure 5.1-1. It consists of a synchronous generator, contactor, and stepup transformer with auxiliary power connections on the line side of the contactor. High resistance grounding is provided for the generator to limit ground fault current levels. The contactor is unfused 5 KV class motor starter with a latching circuit breaker type mechanism. Its 50 MVA interrupting rating is more than needed to clear faults fed by either the generator or the utility system. The stepup transformer is Delta connected at 4.16 KV with a generator WYE connection. At the 12.47 KV utility side, the WYE connection is solidly neutral grounded and has lightning arrestors and a fused load break switch for disconnect and protection of the transformer.

The generator has two controls on its output; real power and excitation. Real power is controlled at the turbine rotor via full

span blade pitch control and excitation is controlled through a voltage regulator and auxiliary equipment feeding the generator shaft-mounted brushless exciter. Power control is inactive for wind speeds below rated wind speed and the Mod-1 output will fluctuate with wind speed and deliver as much power as it can extract from the wind. For wind speeds above rated wind speed, the controller regulates average power output to the level of the system torque rating with an integral plus lag power error type feedback control. The excitation system controls voltage prior to synchronization with the grid. Voltage, power factor, or reactive power control modes may be selected after synchronization. Most operation has been in reactive power control mode with a 250 KVAR delivery to the grid. A stabilizer circuit is also utilized to modulate the excitation in response to hub speed fluctuation.

#### BREMC System Description

The Blue Ridge Electric Membership Corporation (BREMC) 12.47 KV distribution system around Boone, N.C. is shown in Figure 5.1-2. The Mod-1 Wind Turbine is connected to the Howard's Knob Circuit, one of three radial feeders from the Boone Substation. Other connections are possible with manual switching, to feed the Sherwood or Hound Ears substations. The effective impedance seen by the WT generator to an infinite bus equivalent is 0.142 per unit on the originally installed generator base of 2 MVA.

The Boone substation has a 12.47 KV bus voltage regulator and a recloser on each feeder. A voltage blocking device was added to the Howard's Knob circuit recloser to prevent non-synchronous reclosing with the WT generator. The substation transformer rating was raised from 6 MVA to 7.5 MVA in October, 1980, by BREMC and has had a 45 minute peak load of 8.1 MVA recorded in 1981. About 3600 customer accounts are served by the Boone substation of which 660 are on the Howard's Knob circuit. A residence located 1400 ft. from WT is the closest load. The most voltage critical load is a water filter plant with 350 total motor horsepower and 67 percent undervoltage dropout on the circuit breaker. The Bamboo circuit, connected to the Boone 12.47 KV bus, has about 1370 accounts, including a hospital and motor loads at a sewage treatment plant.

#### Utility Requirements

Maintaining constant voltage, service and protecting equipment from faults are the primary operating goals of BREMC. BREMC operation maintains voltage within a 5% band by use of regulators and other devices and limits the size of customer motors that can be full-voltage started. A standard voltage flicker chart, shown in Figure 5.1-3, is appropriate for dynamic voltage fluctuations that are acceptable to most utilities with negligible complaints. The utility grid acts as a large source/sink at constant frequency relative to the WT, and large power fluctuations in the connecting

line are not objectionable to the utility as long as they do not cause objectionable voltage fluctuations in the line.

#### General Operating Experience

BREMC has received no complaints associated with Mod-1 power or voltage disturbances. To quantify the voltage characteristics on the BREMC system, voltage recorders were temporarily installed by BREMC on the 12.47 KV line at the Boone substation and on a circuit supplying power to the meteorological tower which is about 200 feet from the Mod-1 WT. Typical traces from these recorders are shown in Figures 5.1-4a and 5.1-4b respectively.

Figure 5.1-4c shows the line-to-line voltage and phase current at the generator during a transient (breaker closure followed by breaker opening) that occurred during the same period that voltage was recorded at the Boone substation and at the meteorological tower circuit. Although the site voltage fluctuation was almost 7%, the voltage variation at the Boone substation was not discernable on the recorder traces. Most of the recorder voltage change is due to voltage regulator action at the substation, rather than wind turbine produced excitation.

A typical site record of operation at 35 RPM is shown in Figure 5.1-5a. There is a time scale change part way through the record that increases the chart speed by 5 times for better high frequency detail. The power set point was 1000 kW during this time and during the first 60 seconds, the pitch angle is off the electronically controlled stop at about 1.5 degrees in order to regulate. For the balance of the record pitch angle was constant. Power trace oscillation represents wind fluctuations plus drive train natural frequency intermittent oscillation, and 2 per rev response due to tower shadow.

The blade flap bending trace shows the impulsive tower shadow response that occurs once per revolution per blade for the Mod-1 downwind configuration. Voltage fluctuation is limited to  $\pm 1\%$  with frequencies 2 per rev and 1 per rev as a result of the power system stabilizer circuit (speed sensor, voltage regulator). The drivetrain fundamental mode damping is increased by the power system stabilizer action and the resulting voltage fluctuation is well within acceptable limits. The reactive power trace (Figure 5.1-5b) is similar to the voltage trace and was delivering an average 65 KVAR (lagging) to the BREMC system.

The amplitude of 2 per rev (figure 5.1-5a) on the real power trace is about 15% peak to peak which is better than the design value based upon the system dynamic simulations made during the design phase. The on-line behavior of the Mod-1 electrical power system at 35 RPM showed no evidence of instability and exhibited adequate well damped decay in transient wind induced oscillations at the drive train fundamental frequency.



A typical site record of power parameters from recent operation at 23 RPM is shown in Figure 5.1-6. The voltage trace, at the generator bus, varies about 4% overall due to the generator power angle changes resulting from drivetrain oscillation with a less than optimum power system stabilizer circuit. A generator bus variation of 4% corresponds to a critical bus variation of 2.2% which is well within the small gust flicker criteria. Reactive power oscillates about  $\pm 50$  KVAR around the 250 KVAR nominal set point due to drivetrain oscillations also.

The real power and rotor shaft torque traces are in phase which illustrates that drivetrain oscillations are at the torsional fundamental frequency. The frequency of the higher amplitude oscillations is 0.42 hertz, which is near the one per rev frequency of 0.383 hertz. Response at 2 per rev, 0.77 hertz, is also seen at lower amplitude periodically. Shifts in average power at lower frequency are due to wind speed changes or blade pitch changes. Some oscillatory behavior only occurred at 23 RPM with the present control system.

#### Assessment

The Mod-1 Wind Turbine's electrical generation system has performed as expected on the BREMC system. Voltage flicker characteristics are within typical utility limits. Power variation at 35 RPM is about 15% peak to peak and is of no concern to the user utility. Power oscillations result primarily from the 2 per rev response to tower shadow. Electrical performance showed no evidence of instability and exhibited an adequate well damped response to transient wind induced oscillations. At 23 RPM, oscillatory behavior at the drive train fundamental frequency is higher than at 35 RPM.

### 5.2 CONTROLS AND UNATTENDED OPERATION

#### Modes of Operation

The Mod-1 WT was designed to operate in three control modes which are (1) Manual Operation, (2) Automatic Operation and (3) Unattended Operation with Remote Control. The first mode, Manual Operation, enables the on-site WT operator to perform specified maneuvers to perform maintenance and test functions while off line. Included in these maneuvers are (1) orientation of the nacelle at any yaw angle (angle relative to WT vertical axis), (2) orientation of the blades at any angle relative to the hub axis of rotation, (3) orientation of the blade at any pitch angle and (4) rotation of the WT off line at any speed up to and including rated speed. A complete list of functions are shown in Table 5.2-1.

The second mode of operation, Automatic Operation, enables the WT operator at site to start up, set the output power level, obtain data

and shut down the WT. All other control functions are performed automatically without operator intervention. The purpose of this mode is to generate power to the utility grid controlled by an operator located at the WT site. If the wind conditions are within cut-in ( $V_{CI}$ ) and cut out ( $V_{CO}$ ) wind velocity, the WT will generate power at the operator prescribed set point (or less depending upon the wind velocity conditions) in a fully automatic manner.

The third and last control mode is Unattended Operation/Remote Control which enables the operator located at a remote site to start up, set the power output level, and shut down the WT. The purpose of the mode is to operate the WT from the utility dispatcher's office at Lenoir, N.C. 30 miles from the site with no operators at the WT site.

#### Control System Description

To understand how the WT operates in the manual mode and the automatic modes (controlled from the site or a remote location) a description of the overall control system is appropriate at this time. The primary control mechanism of the Mod-1 WT is blade pitch control. Off line the primary control parameter is rotor speed, and on line it is generator power. In general the control system performs all sensing, recording, utility communication, signal conditioning and buffering, and command functions for the WT. A block diagram that illustrates the overall functional arrangement of the equipment to perform the control functions is shown in Figure 5.2-1. The upper block of equipment is located in the nacelle and the two lower blocks are located in the control enclosure. The WT system provides precision analog control of blade angle and yaw orientation in response to wind direction, wind speed, power set point, rotor speed and other operational parameters. The control of most functions is dependent upon multiple inputs and varying "logic" within an operation mode. The Control and Recording Unit (CRU), with its data gathering and processing capability, is the system master controller. CRU logic is used to determine whether to operate depending upon operator commands and control parameters. As an example, the operational envelope of wind speed versus yaw error (difference between nacelle direction and wind direction) is shown in Figure 5.2-2. Manual control is also processed through the CRU with inputs from a keyboard to eliminate human control errors and thus provide maximum machine and personnel safety.

Output power level is controlled by commands to the analog pitch control loop in the Servo Controller. This permits considerable flexibility in operation. A discrete power level can be maintained, the system can track wind speed and maximize power output continuously, and the CRU logic enables the system to come on-line automatically and autonomously when wind conditions permit. Also the control system provides maximum energy capture capability at below rated wind speeds, and maintains safe control of rotor speed at above rated wind speeds. Sufficient diagnostic data can be automatically

recorded so that the cause of shutdowns or anomalous operation can be readily determined. Operating procedures on the Mod-1 Project require that diagnostic data always be automatically recorded.

The control system has the following specific functions:

1. Control the rotor blade pitch angle to startup, supply sub-rated power at wind speeds between 11 and 25.5 MPH and rated power at wind speeds between 25.5 and 35 MPH (nominal).
2. Control the nacelle position through the yaw drive and yaw brake actuators.
3. Condition, buffer, and optionally record sensor signals.
4. Provide operator interface.
5. Provide remote dispatcher control via telephone line.
6. Provide supervisory, alarm, and shutdown control logic.

These functions are performed fully automatically without an operator in attendance at the site to accommodate internal system variables as well as external variables such as wind speed and direction. A detail set of control system functions during startup and generation are shown in Table 5.2-2.

As stated previously, control of blade pitch angle is the predominant dynamic function which directly controls rotor torque. A detail listing of pitch control modes required to operate the WTG with associated operating conditions is shown in Table 5.2-3. The startup sequence to synchronize with the utility grid is shown in Figure 5.2-3.

The second control function positions and holds the nacelle by actuating the hydraulic yaw motors and the yaw brakes. To be able to collect the maximum wind energy possible, the nacelle must be rotated about its vertical axis and aligned with the wind direction. Control logic for the four wind speed regimes is given in Table 5.2-4. If the average yaw error has persisted above five degrees for five minutes, the yaw hydraulic motors are turned on, in the appropriate direction, until the corrected angle is less than one degree. Because of the slow 1/4 degree per second yaw rate, a shorter persistence period is selected as the yaw error increases, as shown in Figure 5.2-4. This change in sensitivity allows higher energy capture during a changing wind direction.

The WT is a complex electromechanical system that must be protected from internal failures and external forces such as wind, ice, snow and temperature extremes. For this reason, fail safe logic has been designed into the WTG controls. The types of shutdowns and the criteria for each shutdown are shown in Table 5.2-5. Backup direct

acting sensors are also provided for overspeed control of the emergency feather and brake systems.

### Experience

One of the main objectives of the Mod-1 Program was the demonstration of the feasibility of remote utility wind turbine control. Communication for remote operation is accomplished at 300 baud via Southern Bell Co. telephone lines. Initial remote control occurred during acceptance testing in February 1980 and was regularly used thereafter when the WT was not allocated to sound and TV interference testing or undergoing major modifications. The majority of the remote control operation occurred between 11:30 PM and 8:00 AM. After remote control operation procedures were established, phone line communications were found to be acceptable. Several dispatchers at BREMC were trained and operated the WT successfully. As experience was gained, additional machine operational parameters were made available to the remote operator to provide a more thorough understanding of the machine operating state. Typical learning problems were experienced including remote terminal hardware failures, occasional switch adjustments and lack of initial operator familiarity with control procedures. Since the WT control logic was based upon a fail safe philosophy with numerous safety checks, personnel and terminal hardware problems did not result in WT misoperation or malfunction.

Significant and beneficial controls information, data and experience were acquired during the WT operation phase. The most significant problem in the WT control system was computer to computer communications. This occurred between the Digital Equipment Corporation (DEC) PDP 11/34 Control and Recording Unit (CRU) and two PDP 11/04's located in the WT Nacelle Multiplexer Unit (NMU) and in the control enclosure Ground Multiplexer Unit (GMU), respectively. The occasional loss of communication between computers resulted in unscheduled WT shutdowns. Operator error message statements such as Nacelle Multiplexer Link Fail, Transmit Buffer Overrun or Connect Fail are printed on the operator terminal when communication failures occur to aid in diagnostic procedures. Communications are controlled by DEC commercial computer electronics boards (DMC-11's) which contain a microprocessor. The kinds of communications failures can be understood by examining the definition of operator error message statements. A Connect Fail occurs when a NMU or GMU fails to return an acknowledgement of an attempt to communicate by the CRU. A Nacelle Multiplexer Link Fail occurs when excessive time for data transfer occurs between either the NMU or the GMU and the CRU. If a successful data transfer occurs, a buffer is released for reuse. When the data transfer is unsuccessful, a buffer is not available for transfer of additional information and a Transmit Buffer Overrun occurs.

Before active investigation and solution implementation began in March 1980 of the "link failure" problem, communication malfunctions

were experienced about 8 days per month. As causes were determined and solutions implemented, malfunctions were progressively eliminated by November 1980. The specific steps taken to eliminate computer to computer communication malfunctions were numerous. The initial step in March 1980 was to install slower byte rate microprocessor DMC-11 boards, 50 kilo bytes per second (KBPS), in place of the existing faster DMC-11 microprocessor boards, 1 million bytes per seconds (MBPS), in the control enclosure-nacelle link. The slower byte rate boards are more tolerant of brief communication lapses. As a result these new boards have reduced link failures but did not eliminate them.

Secondly, in April 1980 the allowable cycle time for computer communication was increased to 350 msec from 150 msec. This reduced link failures further, particularly in the automatic mode. To improve the manual mode, the cycle time was increased to 600 msec in May 1980. Subsequent to this modification, link failures consisted primarily of Transmit Buffer Overruns with the preponderance occurring during lightening storms and yaw maneuvers. In spite of several electrical measurements indicating that the yaw slip ring was performing acceptably, an auxiliary cable bypassing the slip ring was installed for diagnostic tests. Since there were no further link failures while the bypass control cable was installed, it was concluded that the last major cause of communication irregularities was due to a deteriorated slip ring. In May 1981 a slip ring manufacturer's inspection revealed salt deposits on the silver plated contacts. This was the second such occurrence of salt deposit detection on the slip ring contacts even though prescribed cleaning procedures were used about 22 months earlier. Based on the pattern of link failures, it was concluded that the slip rings were progressively being contaminated with a salt deposit. Since the Mod-1 WT is not in a salt air climate, it is speculated that some fluids used in WT operation or maintenance such as hydraulic fluid, may contain a salt additive and might have inadvertently spilled into the slip ring assembly during the initial assembly period. It is planned to investigate the chemical composition of all Mod-1 fluids to confirm this hypothesis. No link failures have occurred with the control system since the May cleaning that can be attributed to the yaw slip ring.

Another lesson learned was the need for qualified and readily available expertise for the computer system preventative and corrective maintenance. Mod-1 site operation records indicate that for the period March - December, 1980 that expert computer technicians were required 13 times. Only during July and August was no preventative and corrective maintenance required. In addition to preventative maintenance every three months, computer services were needed for repair of the line printer, replacement of electronic boards, replacement of disk drive, tape unit repair and remote terminal repair. On call maintenance service was purchased from DEC since they supplied the total computer system including peripherals.

Operation with a mini-computer based control system proved to be highly flexible in making system changes quickly and inexpensively. As an example, after it was concluded that the system rotor speed had to be slowed to reduce the sound generation to acceptable levels, the Central Processor logic within the CRU was easily modified to operate the WT at 23 RPM with a 1200 RPM generator. The control system flexibility was further demonstrated when the WT was operated at 23 RPM with existing 1800 RPM generator (prior to a generator change) while generating power to a temporary load bank without changing control hardware.

Also during routine test, the CRU data base was temporarily changed numerous times in minutes to suit test requirements. Finally, since the Mod-1 WT was the first development vehicle planned to demonstrate the feasibility of a large megawatt WT, a number of unexpected events occurred that required data for analytical investigation. The data archive feature of storing historical operational data on magnetic tape within the Control and Recording Unit proved useful in investigating, analyzing and evaluating all facets of system operation. This system records on tape all "traffic" between the Control and Recording Unit (CRU) and each of the Remote Multiplexer Units (RMU's), all "traffic" between the CRU and BREMC, all communications between the CRU and the on-site operator, and all changes in data states. Recorded data is available for troubleshooting via playback processor when the WTG system is not operating. An RKO 5 disc has been allocated to record operational data for analysis if the magnetic tape recorder is not available.

### Assessment

The Mod-1 WT control system should be more appropriately referred to as an operational control, data acquisition, recording and display system. Based upon the WT system performance during and after the program acceptance test, a general assessment is that the control system performed as designed. The WT was operated successfully in all three modes including the unattended/remote control mode from the BREMC dispatchers office in Lenoir, North Carolina about 30 miles from the Howard's Knob WT site. The control system has the capability of a small conventional power plant in terms of memory and processing speed. When compared to 1981 state of the art WT control techniques, the Mod-1 is considered the equivalent to a second generation wind turbine control system. Perhaps the greatest advantage of the Mod-1 control system is flexibility and this was a key requirement of the nation's first megawatt scale research and development Wind Turbine Generator. With the experience gained from the Mod-1 system, second generation machines are using a more simplified and durable microprocessor.

### 5.3 ENVIRONMENTAL ISSUES

While conducting the initial checkout of the WT during the winter of 79-80, complaints were received from residents in the immediate

vicinity that the machine was producing interference with TV reception and was emitting an annoying sound. Machine operations were restricted to minimize these disturbances to the affected areas while evaluation studies were initiated and established experts hired to properly evaluate these environmental issues. It should be noted that only ten households have complained about noise, and 35 households have noted some TV interference out of a community with a population of over 10,000.

The WT is located on top of Howard Knob (elevation 4420 feet), a heavily wooded mountain in the Blue Ridge Chain of the Appalachian Mountains. Howard Knob is located outside the city limits of Boone (elevation 3266 feet), in Watauga County, in northwest North Carolina near the Tennessee border. It is important to realize that the mountainous terrain (see figure 5.3-1, local map of Boone) surrounding the Mod-1 site has a significant influence on how these environmental issues affect the residents in the community.

#### 5.3.1 Introduction of TV Interference

Throughout 1980, TV reception was investigated and evaluated at areas where complaints of TV interference were received and at other locations in the general area to fully identify the scope of the problem. Communications consultants were used to conduct these test programs and investigations. The geographic orientation of the nine TV channels that the Boone residents watch are illustrated in figure 5.3.1-1, and all of the transmitters are over 46 km from the WT. Table 5.3.1-1, entitled "TV Channels Available in Boone" lists the 9 network channels, station locations, network affiliation, effective radiated (visual) powers, transmitting antenna locations, distances from the WT, and compass bearings.

#### Discussion

The quality of TV reception depends on the signal to noise ratio of the receiver, the receiving antenna used, and the TV signal strength. To determine the quality that is possible in the Boone area, the ambient field strengths were measured at the test sites on all of the available TV channels. Since most of the homes are located in the valleys below the top of the surrounding hills, it was expected that the TV signals would be weak due to shadowing by the terrain. This proved to be the case; and according to the industry specification of the signals needed for high quality service (good reception), the reception of most channels at almost all homes would be classified as poor. The severity of wind turbine interference with TV reception depends on the ratio of the WT's scattered signal strength to the ambient signal strength at the location in question. The TV signal strengths were determined at the base of the wind turbine tower and at the top of the nacelle approximately 150 ft. above the ground. The signal strengths were similar at the nacelle and base of the wind turbine, and the signals received on all channels were quite strong. Because the signal strengths are so

strong at the site of the Mod-1 the reflected signal throughout the interference regions will have a large potential for causing TV interference.

The blades of a wind turbine can interfere with TV reception by producing video distortion. No audio distortion has been observed. When the wind turbine is operating, the interference is caused by the time-varying amplitude modulation of the received signal produced by the rotating blades. In the neighborhood of a wind turbine, the signals scattered by the blades combine with the primary broadcast signal to create a form of time-varying multipath signal, thereby amplitude modulating the total received signal. The modulation waveforms consist of sync pulses, and since each blade of the WT contributes independently, the pulses repeat at twice the rotational frequency of the machine rotor. If sufficiently strong, these extraneous pulses can distort the received picture. When the blades are stationary, the scattered signal may appear on the TV screen as a ghost whose position (separation) depends on the difference between the time delays of the primary and scattered signals. A rotation of the blades then causes the ghost to fluctuate which can result in a more objectionable picture. In such cases, the received picture displays a horizontal jitter in synchronism with the blade rotation. As the interference increases, the entire fuzzy picture shows a pulsed brightening and still larger interference can disrupt the TV receiver's vertical sync causing the picture to roll over (flip) or even break up. This type of interference occurs when the interfering signal reaches the receiver as a result of scattering off the broad face of a blade and is called backward region interference. In the forward scattering region, when the wind turbine is almost in line between the transmitter and the receiver, there is virtually no difference in the times of arrival of the primary and secondary signals. See figure 5.3.1-2 for layout of forward and backward scatter regions. The ghost is then superimposed on the undistorted picture and the video interference appears as an intensity (brightness) fluctuation of the picture in synchronism with the blade rotation. In all cases the amount of interference depends on the strength of the scattered signals relative to the primary one, and the interference decreases with increasing distance from the wind turbine. Interference decreases with increasing distance from the machine, but in the worst cases can still produce objectionable video distortion at distances up to a few kilometers. At a given distance from the wind turbine, the interference increases with increasing frequency; and the interference is worse on the upper VHF channels.

#### Test Results and Tentative Solutions

As a result of the measured data and the analysis performed by the University of Michigan, Department of Electrical Engineering [6, 7], the following observations were made:

1. In the city of Boone and the surrounding area, the ambient field strengths are low on all of the available TV channels. Even



with the WT stationary, the quality of reception is poor; and a high performance antenna is not sufficient to make it good.

2. With the WT operating, varying amounts of TV interference were found at all test areas and on all of the TV channels. One reason for this is the large increase in reflected field strength in the test area due to the Mod-1 wind turbine. With a high performance antenna, the backward region interference observed at the test areas was judged to be acceptable; while in the forward region, the interference was judged to be unacceptable.

The four tentative solutions to the Mod-1 TV interference problem were considered as follows:

1. Restrict machine operating time to avoid operating during prime TV time.

2. Use special high performance antennas at the affected residences.

3. Extend cable TV into affected areas.

4. Rebroadcast television signals via television translators to the affected areas.

Restricted machine operation to avoid prime time television was implemented early in 1980 to minimize the inconvenience of the Boone residents. This was considered only a temporary solution and for the long term would not be economically advantageous. High performance antennas would be economically attractive but would not completely solve the problem. They would eliminate interference in the backward interference region but would be totally ineffective in the forward interference region. The city of Boone and the densely populated areas around the city have access to cable TV. Cable service has not been extended to all the valleys and mountainous areas surrounding Boone and the Howard's Knob area because it is not attractive from a business point of view. These were the areas where the WT caused the TV interference problems.

John F. X. Browne and Associates made an in-depth investigation on the use of TV translators as a potential solution in the Boone area. A TV translator is a rebroadcast station operating with a low power transmitter, usually 10 to 100 watts. The translator converts the conventional VHF TV signals to specific UHF TV channels and rebroadcasts the signals to a specific area. The translator approach depends upon the interrelationship of many variables which include: (1) terrain, (2) power, (3) antenna height, pattern, (4) operating frequency, (5) viewers' reception facilities and (6) localized objects such as buildings and trees which restrict reception. The TV signal quality, within the affected area adjacent to the WT site, provided by the translator system would be equivalent to that provided by a high power TV station in a metropolitan area. These

broadcast stations are considered to be a "secondary" service by the FCC and are licensed on the basis of non-interference with regular TV broadcast stations.

### Summary

Cable TV and rebroadcast via translators both would provide technically adequate solutions to eliminate television interference in the affected areas surrounding the Mod-1 Wind Turbine on Howard's Knob. Special antennas will not solve the TV problem associated with wind turbines. Restricting the operating time for a wind turbine is not considered an acceptable solution to TV interference.

### 5.3.2 Sound

#### Introduction

During the initial checkout operation of the WT in the Fall of 1979, a few complaints were received from local residents that the machine was emitting an objectionable sound. In some instances, it was reported that the sound was accompanied by vibration of residential houses. The character of the sound was described by affected residents as an audible "thump" (similar to a large heart beat) at a repetition rate equal to twice the blade rotational speed. The "thump" occurs when a blade passes behind the tower. In addition to the thump, a typical WT "swishing" sound can be heard in the background that is relatively inconspicuous.

Initial complaints were sporadic and as a consequence difficult to correlate. This inconsistent pattern of complaints was partially due to the seasonal nature of the Boone residential community in the vicinity of the WT. To date ten specific residences within a 2 mile radius have complained about objectionable sound with only two residents complaining persistently. The residents complaining about objectionable sound also complained about TV interference previously described in Section 5.3.1.

As a result of the sound complaints, a joint NASA/BREMC/GE decision was made to limit operation of the WT to daylight hours with the exception of brief periods during the night for necessary sound measurements. To gain community understanding, BREMC conducted informative meetings with affected residents in March of 1980. At that time consideration of a rotor slow down to 23 RPM later in the year was mentioned as a potential method to reduce sound levels. Also during 1980 BREMC released articles to the local press informing the general public of the status of the sound situation.

#### Testing Program and Results

During the early winter of 1979 the Solar Energy Research Institute (SERI) conducted a limited sound survey at the wind turbine site and

near a few affected residences. This survey confirmed the existence of random sound levels at the residences that could be considered the basis for complaints. This is especially true for a rural community that has a very low level of background sound. The initial measurements also revealed that additional in-depth tests would be required to obtain a basic understanding of the sound generation and propagation mechanisms. Initial concerns in addition to the basic sound level were low frequency sound and structural vibration. At this time local atmospheric and terrain characteristics were suspected of intensifying sound at some locations.

The first in a series of three in-depth sound measurement and analysis programs was conducted during February, March and April of 1980. This program was implemented by GE and SERI, and consisted of sound pressure level measurements versus time and frequency. These measurements were made at the WT and in and near the home of a resident that had registered sound complaints on several occasions. In addition to sound measurements, vibration levels in the home of one resident were measured. To evaluate the meteorological effects on sound propagation, Penn State University and the University of Virginia personnel measured atmospheric parameters of temperature and wind velocity as a function of elevation.

The results and basic data from this test program were documented in a report entitled Mod-1 Wind Turbine Generator Preliminary Noise Evaluation<sup>9</sup>. Test data indicated that objectionable sound was basically a sequence of impulses at a blade-passing the tower repetition rate as shown typically in Figure 5.3.2-1. A typical sound pressure level versus frequency curve is shown in Figure 5.3.2-2 as measured within 50' of the WT when generating 1000 kW on February 12, 1980. A comparison of the sound pressure level outside the house of a local resident versus inside the house can be obtained by comparing Figures 5.3.2-3 and 5.3.2-4.

It was concluded from this initial test program that the frequency range of primary interest with regard to complaints was from 5 - 70 Hz. The condition referred to as a "thump" is characterized by an increase in sound especially in the 20 - 30 Hz range. Any objectionable house vibration is due to low frequency acoustic energy in the same frequency range (20-30 Hz). A mathematical model was developed as a sound level predictive tool which suggested that appreciable atmospheric focusing of sound energy could be typical of the Howard's Knob area. Finally, it was predicted that a reduction in rotor speed from 35 RPM to 23 RPM would reduce sound; however, the amount of sound reduction might be marginal with respect to complaints because affected families had been sensitized.

The second series, in the sound measurement program, was conducted with the WT in a temporary configuration operating at 23 RPM generating power into a portable resistor type load bank. The results indicated an average 8 - 10 db reduction in sound power level when compared to the 35 RPM sound power levels, see Figure 5.3.2-5.

These measurements supplied supporting data to continue with the program plan to reduce the WT rotor speed to 23 RPM by replacing the 1800 RPM synchronous generator with a 1200 RPM generator.

The third series in the sound measurement program was conducted in January 1981 after the 1200 RPM generator installation when the WT was generating power into the utility grid at 23 RPM. Statistical data was recorded in the 31.5 Hz octave band near field (approximately 240 - 270 feet from the WT center) at three locations and in the far field at two of the local residences. Data was recorded continuously and statistical distributions were automatically generated for half hour periods so that sound pressure level data could be plotted versus the percentage of the time that a specific level occurred. A typical curve is shown in Figure 5.3.2-6 with a 50 percentile near field (at the WT) sound pressure level of 71 db compared to a minimum ambient level of 54 db.

The results of this test program have been reported in a document entitled Mod-1 Wind Turbine Generator Statistical Noise Studies<sup>2</sup> by R. J. Wells of the General Electric Company. At one residential area, the average sound pressure level (50 percentile) varied from 64 db when a complaint was registered to 51 db when no complaints were received, see Figure 5.3.2-7. At the second residential location the average sound level (50 percentile) was 49 db while on-line, see Figure 5.3.2-8.

Based upon the results of this test phase, it can be concluded that the sound level in the 31.5 Hz octave band is a reasonable choice for a convenient measure of wind turbine sound. The sound levels in the near field are essentially constant for a given yaw angle and wind velocity. The sound levels measured in January 1981 correlate closely with the prior 23 RPM load bank tests from the summer of 1980. Much of the time the far field levels in the 31.5 Hz band are about as would be expected based upon the assumption of spherical divergence. No complaints occurred under these conditions. The condition referred to as "thump" seems to be caused by occasional atmospheric focusing due to unusual wind and temperature gradients. At one far field location, measured levels as much as 25 db above that expected by spherical divergence occurred, and in such cases the far field level exceeded the near field level.

### Assessment

Complaints about objectionable sound resulting from WT were restricted to an area with a radius of two miles and to 10 residents. Only two of these residents complained persistently. Based upon the concerns of the local Boone residents, WT operation was curtailed during early evening hours with a few exceptions. The character of the sound is repetitive, similar to a heart beat. Reducing the rotor speed to 23 RPM reduced the sound level about 10 db near the WT as predicted. At 23 RPM statistical analysis of sound measurements at the WT indicate that the average sound (50

percentile) was about 70 db and that 1 percent of the time the sound level was about 77 db. Adjacent to one of the local residents who was more persistently annoyed the average sound level was about 52 db, and 1 percent of the time exceeded 60 db for the test period. At the same location during a one hour and half period (1-1/2) when a complaint was received, the average sound level was 63 db and 1% of the time exceeded 77 db. The measured sound levels at local residences which are equal to or greater than sound levels measured at the WT on rare occasions substantiate the notion that atmospheric focusing is a significant factor in causing the limited number of complaints at Boone. Another interrelated factor in causing sound complaints is WT produced TV interference that creates an awareness on the part of a sensitized resident of WT operation via a visual medium.

#### 5.4 Wind Turbine Performance

The performance of the Mod-1 Wind Turbine was originally reported in 1980 in reference [12]. The experimental data used in this performance analysis of Generator Power Output vs. Wind Speed @ the Hub was preliminary at that time, but the machine was operating as predicted. Figure 5.4-1 illustrates the same plot as the above reference except that there are substantially more data samples included in each plotted point. The machine's performance follows the design prediction very well. A few data points from the reference plot and figure 5.4-1 are above the design line indicating that the machine has a higher overall efficiency than was originally predicted.

As expected losses occur in the drive train and rotor of the machine. The generator, bearings and gearbox are standard components and their manufacturers have well documented efficiency curves.

#### Assessment

The resulting efficiency increase is attributed to a higher than predicted aerodynamic performance of the blades. The original Mod-1 Wind Turbine performance calculations may have been conservative due to the lack of blade aerodynamic performance data particularly with regard to blade surface effects. A more detailed performance analysis of the Mod-1 Wind Turbine has been reported in reference [13].

#### 5.5 DRIVE TRAIN

##### 5.5.1 Drive Train Dynamics

##### Introduction

In March 1980, trade off studies were initiated to identify near term practical methods of reducing the sound level emitted by the machine. Reducing the rotor speed was selected as the option to be

implemented. This change could be accomplished by changing synchronous generators, (1800 RPM to 1200 RPM), thus reducing the rotor speed from 35 to 23 RPM. This option was selected because it yielded the best set of advantages: (1) Minimum changes to the machine; (2) minimum time schedule to complete the machine changes; (3) minimum costs; and (4) high probability of solving the sound problem. A solution had to be selected early to initiate hardware procurement for installation during the fall of 1980 for subsequent testing during the winter of 1980. Selecting the reduced rotor speed option in March 1980 provided six months to procure the hardware and schedule the change.

### Discussion

During the analysis and design period for the reduced rotor RPM option, it was realized that the once per rev excitation frequency (0.383 Hz) is close to the drive train natural frequency of 0.41 Hz when operating the WT at 23 RPM. This situation presented the possibility that if the blades were not well balanced or aerodynamically trimmed, an undesirable 1 P response might be experienced in the drive train. The WT was operated at 23 and 35 RPM in a manual mode and synchronized to the utility grid at 35 RPM without any indication of an imbalance between blades. Therefore, since there was not a positive indication of an impending problem associated with this proposed change, it was decided to proceed with the rotor speed reduction.

During the period of time when the WT was operated at 35 RPM, the machine performed well, was compatible with the utility grid, and was dynamically very stable. When the reduced RPM option was completed, our concerns during the analysis and design period became a reality. During gusty wind periods, the machine experienced power swings of  $\pm 40\%$  about the control set point during intermittent time periods. While this did not affect the utility or its customers because of the relative size of the utility and power generated by the wind turbine, power swings of this magnitude are undesirable. Power swings of this magnitude on the WT would reduce the life of some components primarily the gear box, and on commercially produced wind turbines would add unnecessary capital equipment costs to withstand 40% fatigue type overload conditions. To avoid potential damage to the WT gear box, the power set point was temporarily limited to 1,000 KW until the power swings could be reduced.

Wind turbine generators have a lightly damped torsional mode generally below 1 Hz which is determined by turbine inertia and shaft stiffness. The generator inertia for the 35 to 23 RPM change increased from 50.5 lb-ft-sec<sup>2</sup> to 69.7 lb-ft-sec<sup>2</sup>, which was an insignificant drive train inertia change. Frequency and damping ratio of the first torsional mode are influenced by four factors: (1) drive train; (2) power regulation; (3) power system stabilizer; and (4) hub speed feedback. The first torsional mode of the WT drive train is 0.41 Hz, which primarily represents the movement of the hub

and blades against the effective stiffness of the shafting, gearbox, and generator connection to the power system. Since the electrical stiffness between the generator and utility power system is higher than the mechanical stiffness between the rotor and generator, the displacement of the turbine rotor on the first torsional mode is much greater than the displacement of the generator rotor. The stiffness ratio of utility power system to the wind turbine drive train system is 8.33 to 1. Electrical damping at the generator is difficult because the generator rotor is a minor part in the displacement caused by the first torsional mode. Shaft damping can be effective but would require extensive structural changes.

### Assessment

Damping at the rotor can be achieved by a more active blade angle control. A control system analysis of a Mod-1 system indicated that increasing damping of the first torsional mode from 5% to 25% of critical damping could be achieved by adding a signal in phase with hub speed deviation to the output of the blade pitch angle controller. This would require a more active pitch hydraulic system which could increase maintenance on this system at some time in the future, since the system was not originally designed for the more active duty cycle associated with the added hub speed control signal.

During January 1981, the WT was operated at the reduced power set point while sound measurements were made to evaluate the machine operating at 23 RPM. The program operating schedule called for completion of the evaluation and demonstration of the 23 RPM control system problem in February 1981. A problem developed in the drive train on January 20, 1981, which terminated operations, which will be discussed in the next section.

### 5.5.2 Drive Train Problem

#### Introduction

On January 20, 1981, the WT experienced a failure of 22 studs in the drive train. Specifically these studs attached the low speed shaft gear coupling to the rotor hub. Figure 5.5.2-1 illustrates the general drive train arrangement on the WT and identifies where the bolted joint is located. When the rotor hub separated from the low speed drive shaft and remaining portion of the drive train, the safety system initiated feathering of the blades which stopped the rotor/hub and opened the circuit breaker to the utility which electrically isolated the generator from the grid.

#### Discussion

The machine was safely secured and sustained relatively minor damage during the safety system controlled shutdown. The torque plate which is mounted on the rotor hub assembly contained the 22 broken ends of the studs within helicoil inserts. The remaining portions of the

broken studs were recovered from the lower portion of the bedplate. The outer sleeve of the gear coupling was damaged during the shutdown and will require replacement. This shaft coupling outer sleeve rapped the pitch rod adjusting mechanism during the shutdown. These adjustment mechanisms and the "uniball" end fittings must be replaced. The instrumentation and power wiring bundle and conduit within the low speed shaft was severed when the coupling/low-speed shaft separated from the rotor hub and must be replaced.

Figure 5.5.2-2 illustrates a section view of the hub/shaft interface and locates the studs that failed. During assembly personnel access to the backside of the hub torque plate was limited which necessitated the blind connection. Figure 5.5.2-3 illustrates the stud/helicoil installation in the rotor hub torque plate/low speed shaft coupling joint. Self locking stainless steel helicoils inserts were used to increase the thread strength in the mild steel torque plate. The studs pass through clearance oversized holes needed for helicoil installation in the torque plate before engaging the helicoil insert.

The rotor hub torque plate to coupling interface was designed as a conventional friction joint with the fastening studs providing the preloading to a joint capacity of 885,000 ft-lbs. The drive train had a rated torque capacity of 442,000 ft-lbs which yields a joint safety factor of 1.99. The drive train has a slip clutch adjusted to slip at a setting of 829,000 ft-lbs which would slip at 93% of the joint rating.

Metallurgical analysis of the failed studs revealed that high strain; predominantly low cycle bending fatigue was the cause of the stud fractures at the helicoil end. The stud material was found by metallurgical analysis to be of excellent quality and free of any defects. After the failure, examination of engineering log books indicated that the studs were not properly preloaded which is believed to result in a joint torque capacity of 683,000 ft-lbs or only 77% of its original design value. The stud geometry and spacing in the oversized torque plate and gear coupling holes would allow a relative rotation of 1 degree between the torque plate and gear coupling. Torque loading of the drive train forced relative rotation which in turn failed the studs via bending fatigue. A second major contributing factor that the slip clutch malfunctioned on several occasions before it was discovered operating improperly. A third contributing factor was occasional torque loadings in excess of the design values including both peak and cyclic torque overloads. The principal cause of this failure can be attributed to improperly installed studs and a malfunctioning slip clutch which was installed as an overtorque protection device.

#### Assessment

The failed joint has been fully reviewed and analyzed and a suitable repair method identified. The drive train damage can be repaired for



the most part in the nacelle with only the low speed shaft and pitch change mechanism being removed. The rotor hub torque plate rework will require precision machining, and several sources that can provide this type of service have been identified.

### Specific Recommendations

Basic friction-torque joints are desirable in future wind turbine applications because they are lower cost than other conventional designs. Also, some drive train designs may have no other alternative than to use friction torque joints. Designers in designing this type of joint should consider providing a friction torque capability for all specified loads with a safety factor of 2.5 as a minimum. In addition, the designer should assume that the joint will slip near limit loads and the fasteners will be carrying the torque load in shear. Clearances around fasteners should be minimized so that the fasteners will be more uniformly loaded. Designers are urged to be conservative in selecting a friction coefficient for this type of joint. Through joint fasteners that are positively locked are recommended, and helicoils should be avoided in this type of joint. Lastly, the fastener tensioning technique must be verified by test and verified at installation by proper inspection. Using a slip clutch as a overtorque safety device in wind turbine is considered acceptable. Particular attention must be paid to the application, installation and understanding all facets of its operation and maintenance. Designers must obtain enough detailed information from the slip clutch manufacturers to fully understand the operation and limits especially if the unit is not a shelf item or a shelf item has been modified.

## 5.6 PUBLIC REACTION AND ACCEPTANCE

### Introduction

Over the past two years, the public reaction has been favorable toward the Mod-1 Wind Turbine Project. This included the vast majority of local people who live in and around Boone near the turbine site. In the regional area of North Carolina and over the rest of the country, people were supportive; but not as interested in the project as the Boone residents. Nationally, the Mod-1 Project was recognized as the first operational megawatt sized wind turbine in the world.

### Discussion

There have been many articles in the North Carolina and Boone papers reporting on the various phases of the Mod-1 Project over the past two years. Occasionally, national publications such as Time Magazine, the Wall Street Journal, Aviation Week & Space Technology, have had articles on the Mod-1. Trade journals including 1980 Generation Planbook and Electrical World have published material describing the Mod-1 Wind Turbine. Newspapers outside of North

Carolina such as The New York Times, Washington Post, Cleveland Plain Dealer, and Philadelphia Inquirer and others have published articles about the project. The North Carolina television stations have also reported numerous times on the Mod-1 Program.

Various management personnel from the Blue Ridge Electric Membership Corporation have given an average of over 100 talks per year around the state of North Carolina to various civic, religious, and public organizations during the first two years of the project. The Blue Ridge management has reported that the groups that they have talked to as well as the general Boone residents have been very supportive of wind power as a form of generating electrical energy. The academic community from Appalachian State University, a local college, have been very supportive of wind power by conducting energy seminars including wind energy reviews and are conducting their own wind energy projects which consists of operating a small horizontal axis wind turbine.

The Mod-1 site is a continual attraction to visitors to the Boone area and residents from the southeastern part of the United States. Approximately 4000 per year informational brochures on the Mod-1 have been passed out to site visitors during the normal working hours by maintenance personnel. During the fall of the year when the leaves are changing color in the local mountains, 1500 visitors have visited the site on several successive weekends. This caused traffic problems on the WT access road and local off-duty police were hired to control the traffic flow. Many foreign visitors from South America, Asia, and Europe as well as United States government and industry leaders have visited the site. In fact large numbers of foreign and domestic VIP groups occasionally have been disruptive to meeting Mod-1 Program Schedules. School classes, youth groups, professional organizations etc. are continually scheduling visits through the local Blue Ridge Electric Membership Corporation District Manager.

#### Assessment

The public reaction to the Mod-1 Wind Turbine Project has been demonstrated continually by the number of visitors to the site. The people have clearly expressed to Blue Ridge and site personnel their desire for pollution free electricity that is not dependent on foreign produced oil. The local people have expressed their desire to see the WT operating more of the time. The wind velocity is highest during the evening and early morning hours; therefore, they haven't observed it during much of the operating time. In addition configuring for testing causes periods of time when the WT can't be operated. In the opinion of the personnel involved with the WT from Blue Ridge, NASA and General Electric Company, the public, who have visited the site and the local Boone residents, are definitely in favor of producing electrical power via wind turbines generators.

## 6.0 CONTRIBUTIONS TO WT TECHNOLOGY

### Introduction

Since the Mod-1 WT was the first modern megawatt class machine that had as its purpose research and development, a number of major contributions have been made to WT technology. These contributions resulted both from deliberate investigative efforts as well as from unexpected problems that occur during any "first of a kind" endeavor. The important WT technology developments that can be attributed to the Mod-1 program include innovative low cost WT design concepts and metal and composite blade fabrication/process techniques. The Mod-1 was the first remote unattended 2 megawatt WT to synchronize, generate power to a public utility system, and be controlled by a utility dispatcher. Computer codes were verified for dynamic and loads analysis, performance prediction and electrical stability analysis. These will be useful for future generation designs of megawatt class systems. Environmental impact issues, such as sound generation and TV interference, were experienced, evaluated, and solutions for wind turbines identified. And finally, a host of "lessons learned," including the importance of optimizing an installation site to WT characteristics, have been reported in the literature for the benefit of the WT industry.

### Innovative Design Concepts

Just after the completion of the Mod-1 design, a Mod-1A configuration was designed and reported to the WT industry at a NASA workshop in March of 1979 that synthesized the innovative concepts that were a by-product of the Mod-1 design experience. These low cost concepts identified on the Mod-1A which were beyond the scope of the Mod-1 specification, have been incorporated in second and later generation WT's. These innovations are a soft tower, partial span control, a teetered hub and an upwind rotor. The utilization of these concepts with others, has resulted in cost effective WT's which are the keystone of the emerging commercial market.

### Blade Manufacturing Technology

The manufacturing of the Mod-1 rotor blades, modern industry's initial attempt to construct a blade of 100 foot in length, established the fabrication technology for welding and stress relief of steel blades for the WT industry. The Mod-1 blades have performed successfully experiencing in excess of three quarters of a million cycles and "know how" from these blades has been incorporated in second generation steel welded blades. Also two composite fiberglass rotor blades designed specifically for Mod-1 have recently been manufactured, further establishing the Transverse Filament Tape (TFT) manufacturing process. One hundred foot blades once regarded as a challenge in the 1970's will be commonplace in the 1980's primarily as a result of the knowledge gained by the Mod-1 design and manufacturing experience.

### Power Generation Feasibility

In the area of performance, the Mod-1 demonstrated that a multi-megawatt wind turbine could be successfully synchronized with a utility grid and generate stable electrical power meeting utility quality standards. Secondly, the Mod-1 demonstrated that an unattended WT could be operated remotely in conjunction with a utility system by a utility dispatcher in a fully automatic mode. Although power level varies significantly with wind speed and direction fluctuations, voltage flicker was well within utility standards. Transients associated with initial synchronization and WT shutdown exhibited a stable, acceptable behavior.

### Environmental Impact

Perhaps the most significant contribution to WT technology resulted from the environmental impact of the Mod-1 in the Boone, North Carolina community. In the Fall of 1979, shortly after dedication, unanticipated complaints from local residents about objectionable sound and television interference caused by the WT were received by BREMC, the local utility. As a result, extensive efforts were conducted to characterize, establish standards, and solve sound and TV interference problems at Boone. The specific knowledge developed on the phenomenon was then incorporated into the second generation wind turbines.

In regard to sound, extensive measurements were made in the immediate vicinity of the WT and at remote residential locations, intermittently and continuously, and during daylight and evening hours at various weather conditions. These measurements were made at various WT rotational speeds, on line and off. The most important favorable impact of the Mod-1 experience at Boone resulted in an acute awareness throughout the WT industry of the WT noise generation problem. In addition to solving the Boone problem by reducing the rotor speed, this unexpected site specific environmental concern provided the impetus to characterize WT sound generation, develop predictive computer codes and establish WT sound standards. The body of knowledge that evolved from the Mod-1 experience is being incorporated in future generation designs and in utility site selection criteria.

A parallel story about TV interference unfolded in much the same manner to WT generated sound. Although not totally unexpected because of prior experience at Mod-OA sites, TV interference caused complaints within a 1-1/2 mile radius due to terrain which consequently restricted WT operation. An extensive measurement program was conducted that evaluated basic signal strength and interference characteristics. The results of the test program lead to the evaluation of three tentative solutions utilizing high gain residential antennas, cable TV and VHF to UHF rebroadcast translators. In the interim, however, the TV interference problem

was eliminated by restricting the turbine operation to other than prime TV time. Thus far Mod-1 has contributed to the understanding and identification of solutions to this critical environmental problem that will affect future WT siting decisions.

## 7.0 CONCLUSIONS

### Power Generation on Utility Grid

The WT has generated electrical energy within utility standards in a stable and well controlled manner. At 35 RPM transient wind conditions have had no adverse effect on the power generated or the machine. At 23 RPM the power generated was still within utility standards but the drive train was responding to its fundamental frequency.

### Controls and Unattended Operation

The controls system initially presented a succession of minor problems and they were eventually solved. After the program acceptance tests, the control system performed flawlessly as designed. The WT was operated successfully in all modes including manual operation, automatic operation, unattended operation, and unattended remote control from the BREMC dispatchers office in Lenoir. In addition, the versatility of the control system allowed testing in various unconventional machine configurations during the Mod-1 Test Program.

### TV Interference

Cable TV and rebroadcast via translators both provide excellent solutions to eliminate TV interference caused by wind turbines. Many areas of the country already have these systems installed. Because of the recent strong interest by the business community in providing these communication systems, cable TV and translator systems are being installed at a rapid rate throughout the country. This will be a definite advantage to the users of wind turbines.

### WT Generated Sound

As a result of the sound test program conducted on the Mod-1, the sound emitted by WTs is now defined, understood and predictable. In addition, acceptable sound level standards for WTs are being established for WT manufacturers use. The meteorological effects on sound propagation and focusing of sound energy information will be an important criteria in WT site selections.

### Drive Train Dynamics

When the WT was operated as originally designed at 35 RPM, the machine ran well, was compatible with the utility, and was dynamically very stable. When the WT was test configured to reduce

the sound emitted at 23 RPM, the machine responded to its fundamental frequency in high turbulent winds, was compatible with the utility and was dynamically stable. A solution to the 23 RPM drive train fundamental frequency problem would be a more active blade pitch control system. This would increase the drive train damping which would permit the drive train to operate with less excitation of the first torsional mode in turbulent winds.

#### Public Reaction and Acceptance

The NASA, BREMC and GE personnel involved with the Mod-1 Program believe that the public who they have talked with at the site as well as the local residents around Boone have a very positive attitude toward using wind turbines to generate electrical energy. The large number of visitors and groups from foreign countries and the United States visiting the Mod-1 site in this remote mountain community attests to the popularity of this method of energy conversion.

#### Contributions to WT Technology

The Mod-1 Program has made substantial contributions to the development of WT technology. GE through the experience gained during the design phase of the program developed many low cost design concepts for the benefit of the wind turbine industry. Metal and composite blade manufacturing technology was also developed. The Mod-1 first demonstrated that a megawatt sized WT could be operated in an unattended fully automatic mode and generate utility quality power into a public utility system. Analytical computer codes for predicting wind turbine dynamic and loads analysis were verified from Mod-1 data. A significant contribution to the wind turbine industry was the discovery that the Mod-1 had an environmental impact on the community.

#### Project Objectives

The specific Mod-1 project objectives, listed below, which were a part of the Federal Wind Energy Program, have all been achieved.

- o Provided megawatt sized wind turbine operational and performance data.
- o Demonstrated unattended, fail-safe operation.
- o Involvement of utility as user and operator.
- o Identification of maintenance requirements.
- o Industry involvement in design, fabrication, and installation of the WT.
- o Identify components/subsystems modifications to reduce cost, improve reliability and increase performance.

- o Assess public reaction/acceptance of large wind turbines.
- o Demonstrate compatibility with utility requirements.

## 8.0 ACKNOWLEDGMENTS

There have been many participants involved with the Mod-1 Program that have contributed to its success, and we thank you all for your excellent support which is appreciated. Particular thanks is extended to Mr. R. Puthoff, NASA-Lewis Research Center and Mr. R. Barchet of the General Electric Company for their outstanding contributions to the program. Successful completion of the program would not have been possible without the much needed project support from Messrs. G. Ayers, Jr., and R. Bumgarner of BREMC in North Carolina.

The following individuals, who are nationally recognized experts, and their organizations have made major contributions to portions of the program. We appreciate their excellent support and adjusting their busy schedules to be available when needed for conducting field tests, analyzing results, developing analytical prediction techniques, writing reports and attending meetings.

- o Messrs. D. S. Sengupta, T. A. B. Senior, J. E. Ferris of the University of Michigan.
- o Mr. J. F. X. Browne of John F. X. Browne Associates.
- o Mr. R. J. Wells of GE Corporate Research and Development
- o GE Corporate Research and Development Staff.
- o Mr. N. Kelley of Solar Energy Research Institute.
- o Messrs. G. C. Green, D. G. Stephens of NASA Langley Research Center.

We thank the two Mod-1 blade contractors and their project managers, Mr. J. Van Bronkhorst, Boeing Engineering and Construction, and Mr. W. Batesole, Kaman Aerospace Corporation, for their contribution to the program.

We also thank Messrs. J. Brown of GE and T. Miller of BREMC, who were at the site during the machine's assembly and continued during the operational period, for their outstanding support.

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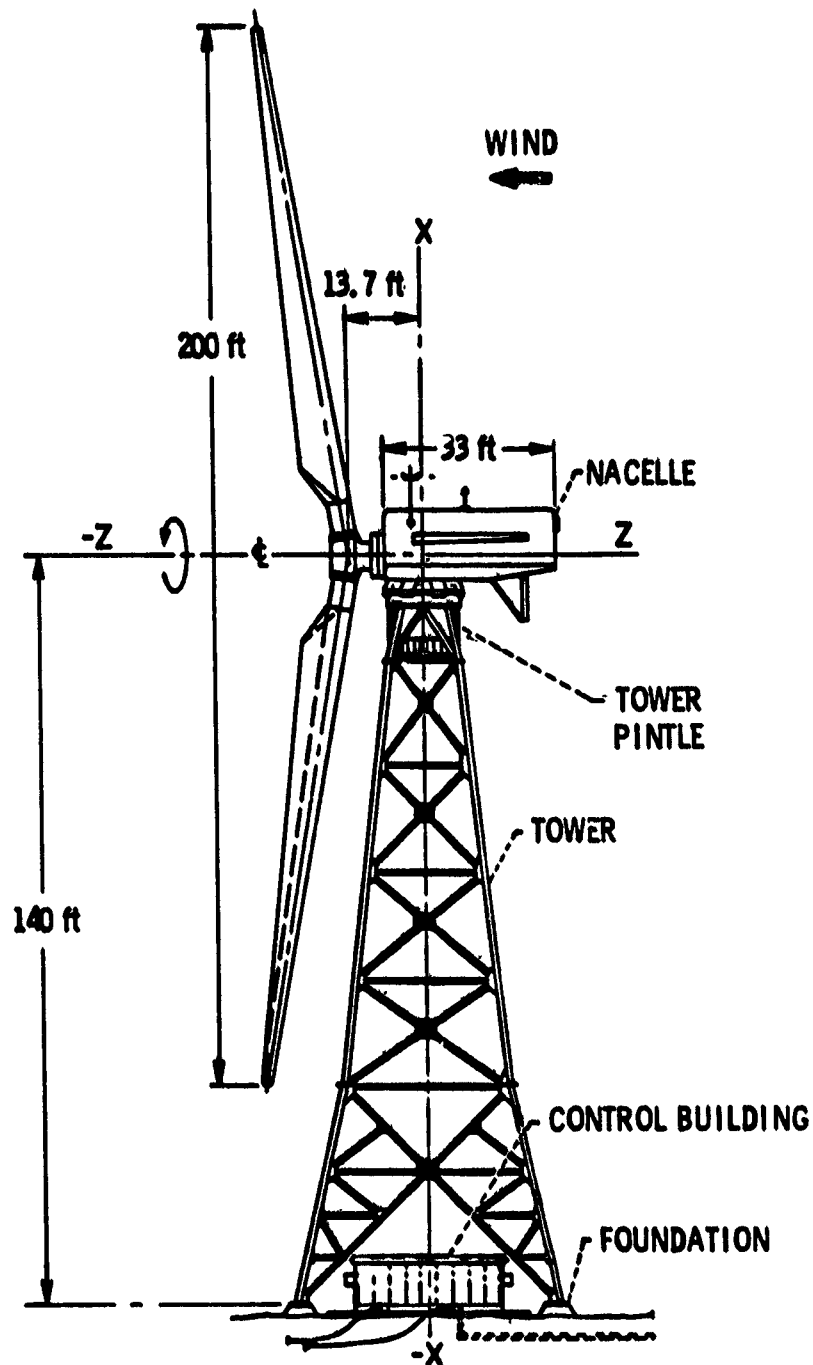


Figure 4.1-1. - Mod-1 2000-kilowatt wind turbine.

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NASA  
C-79-2497

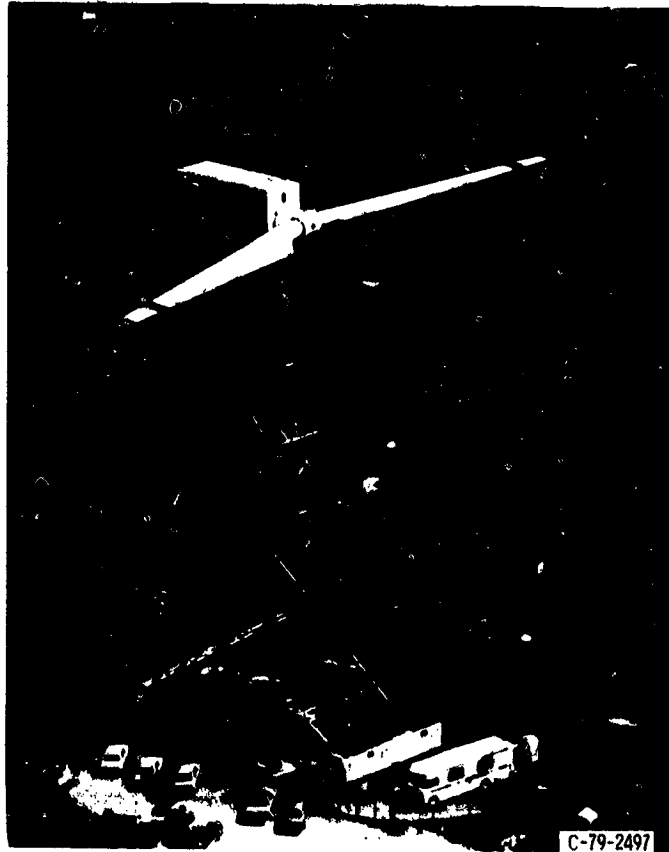


Figure 4.1-2. - DOE/NASA 2000-kW experimental wind turbine, Howard's Knob, Boone, North Carolina.

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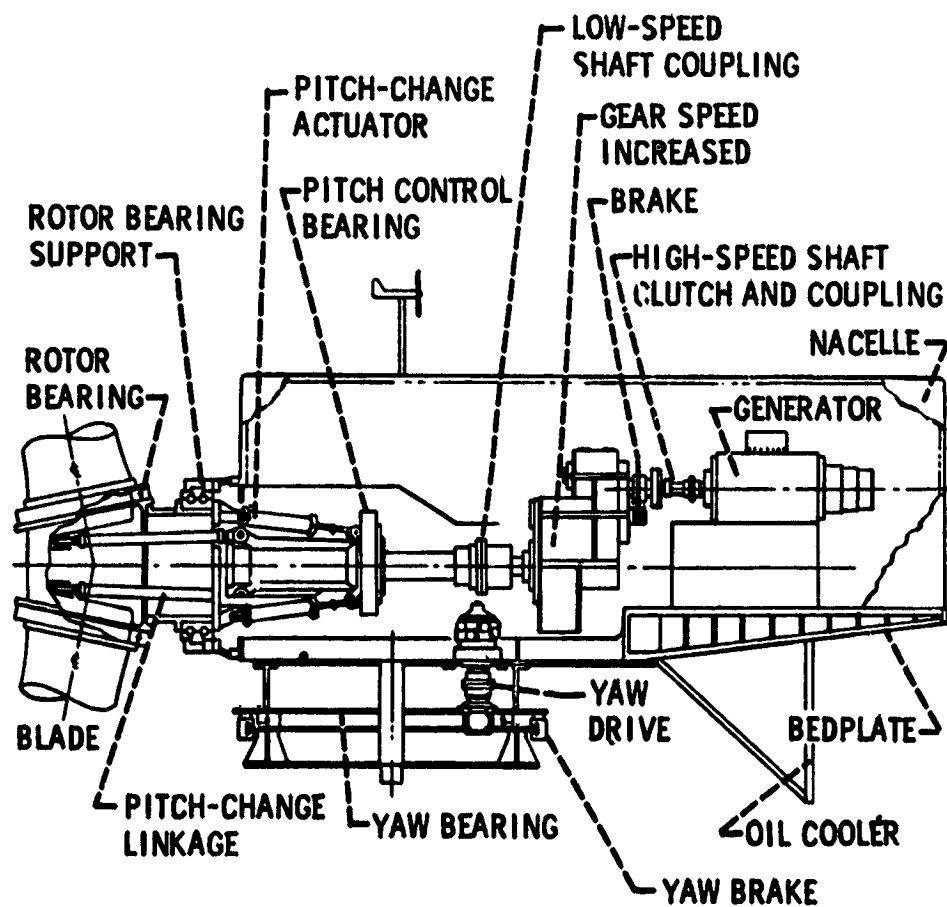
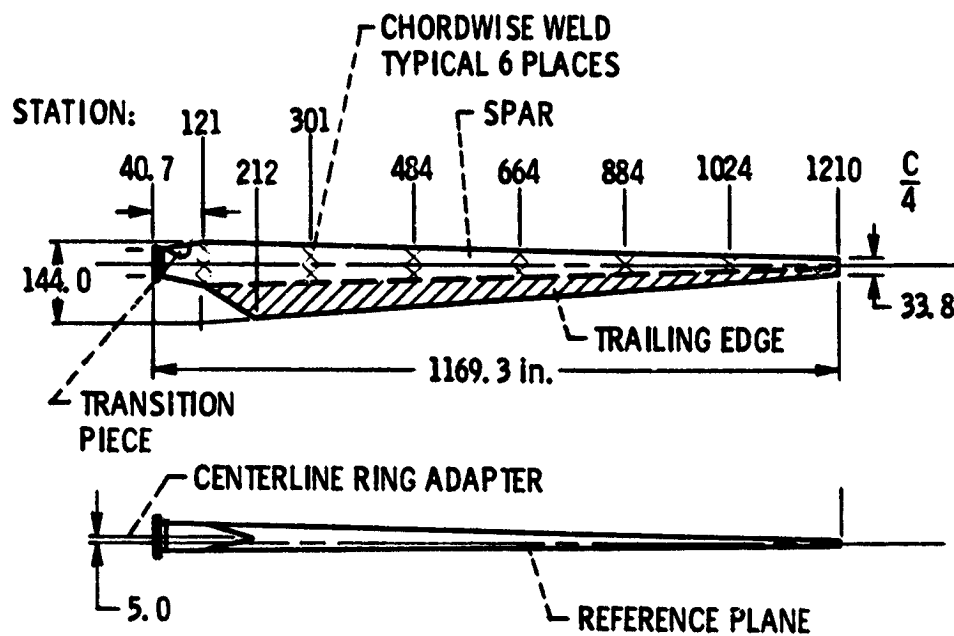
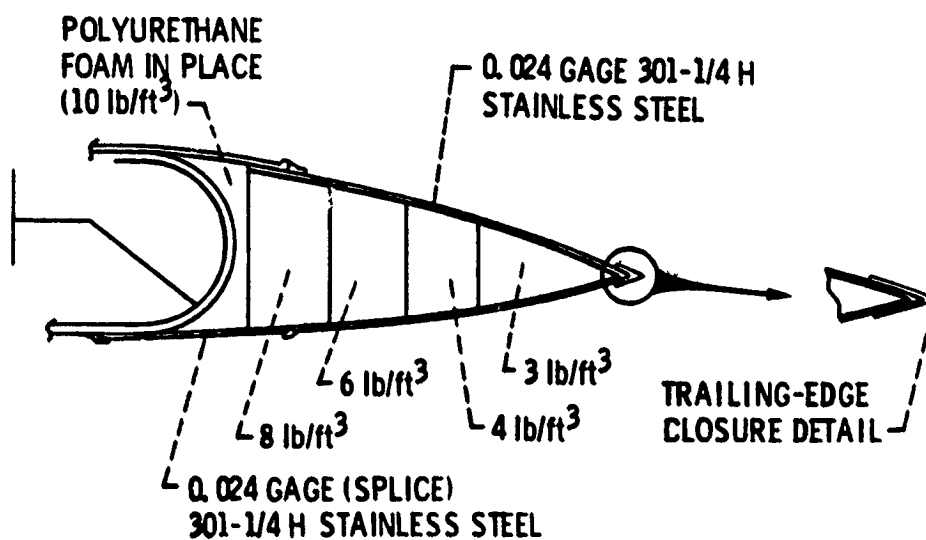


Figure 4.1-3. - Schematic diagram of the Mod-1 wind turbine assembly.

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(a) BLADE GEOMETRY.



(b) TRAILING EDGE.

Figure 4. 1-4. - Blade and trailing-edge geometry.

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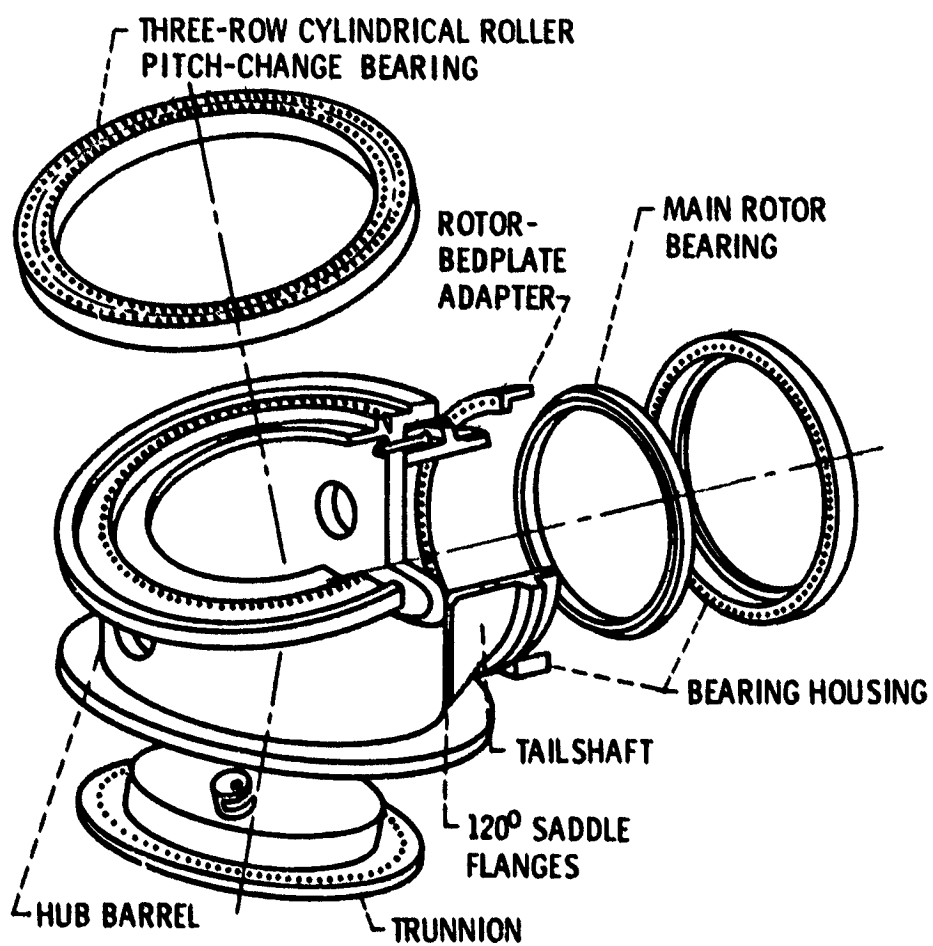


Figure 4. 1-5. - Hub assembly.

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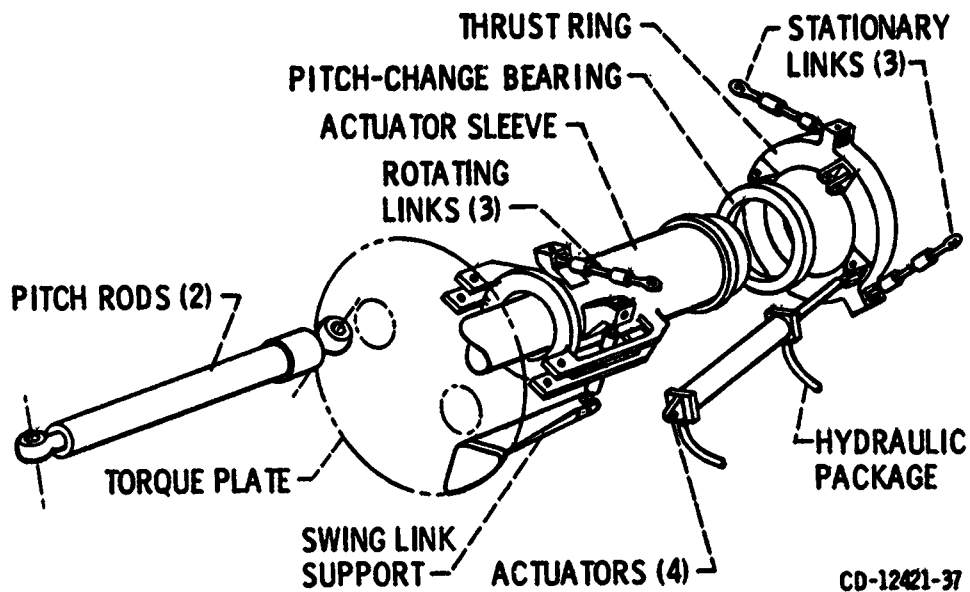


Figure 4.1-6. - Pitch-change mechanism.

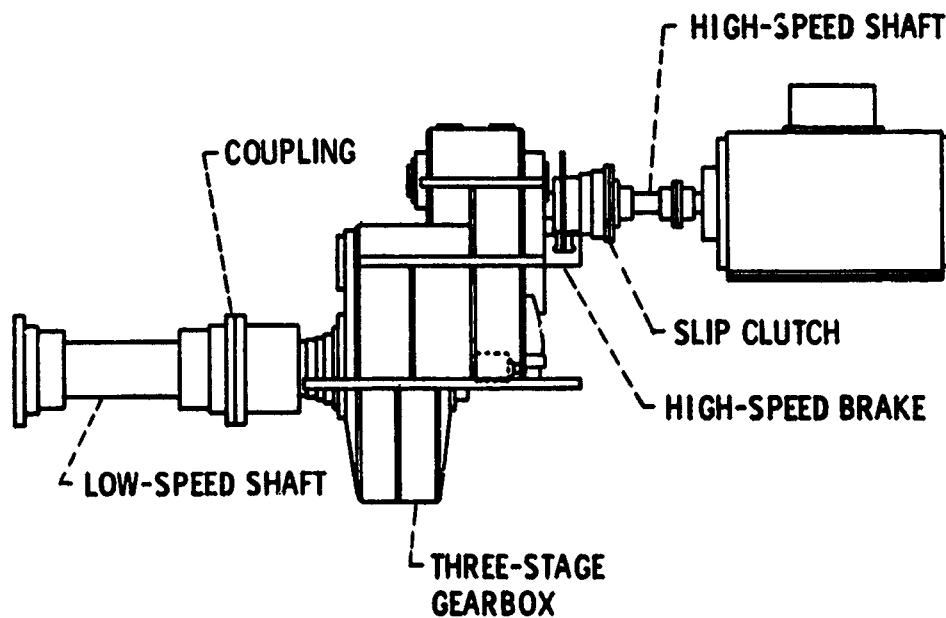


Figure 4.1-7. - Drive-train assembly.

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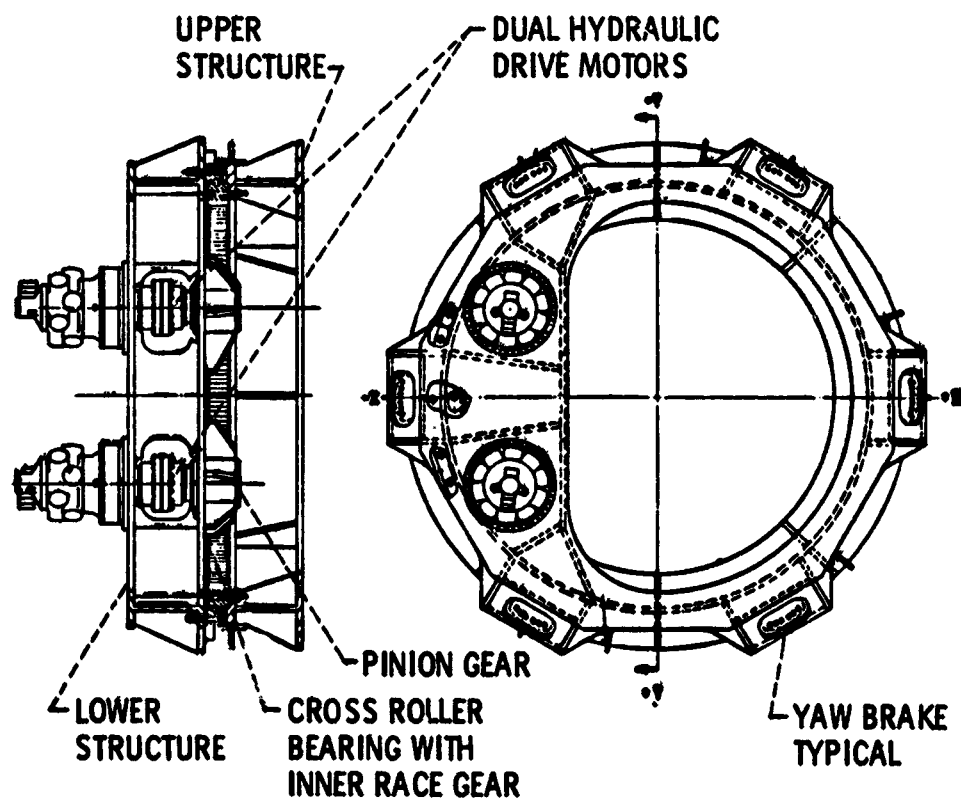


Figure 4.1-8. - Yaw drive assembly.



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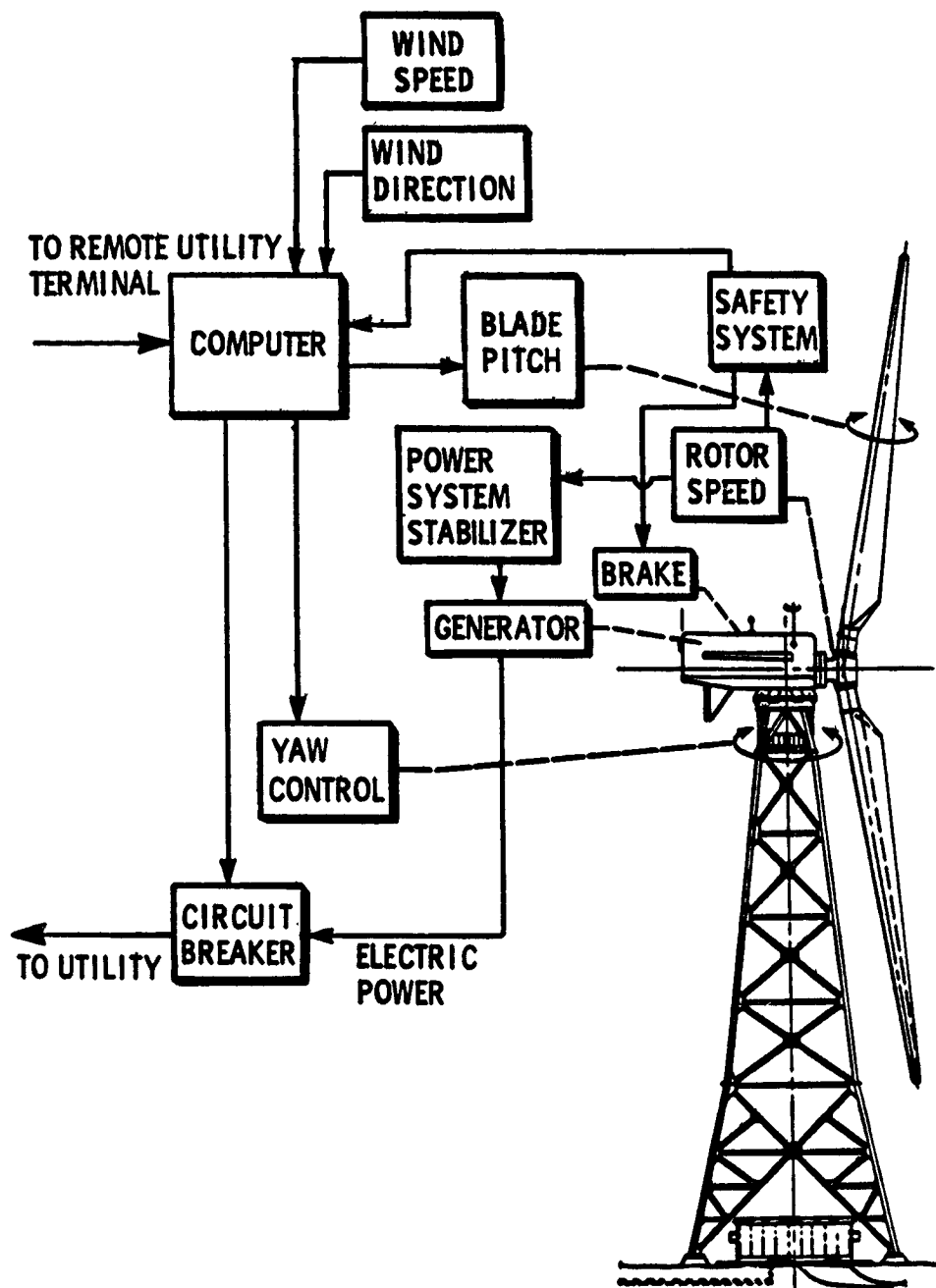
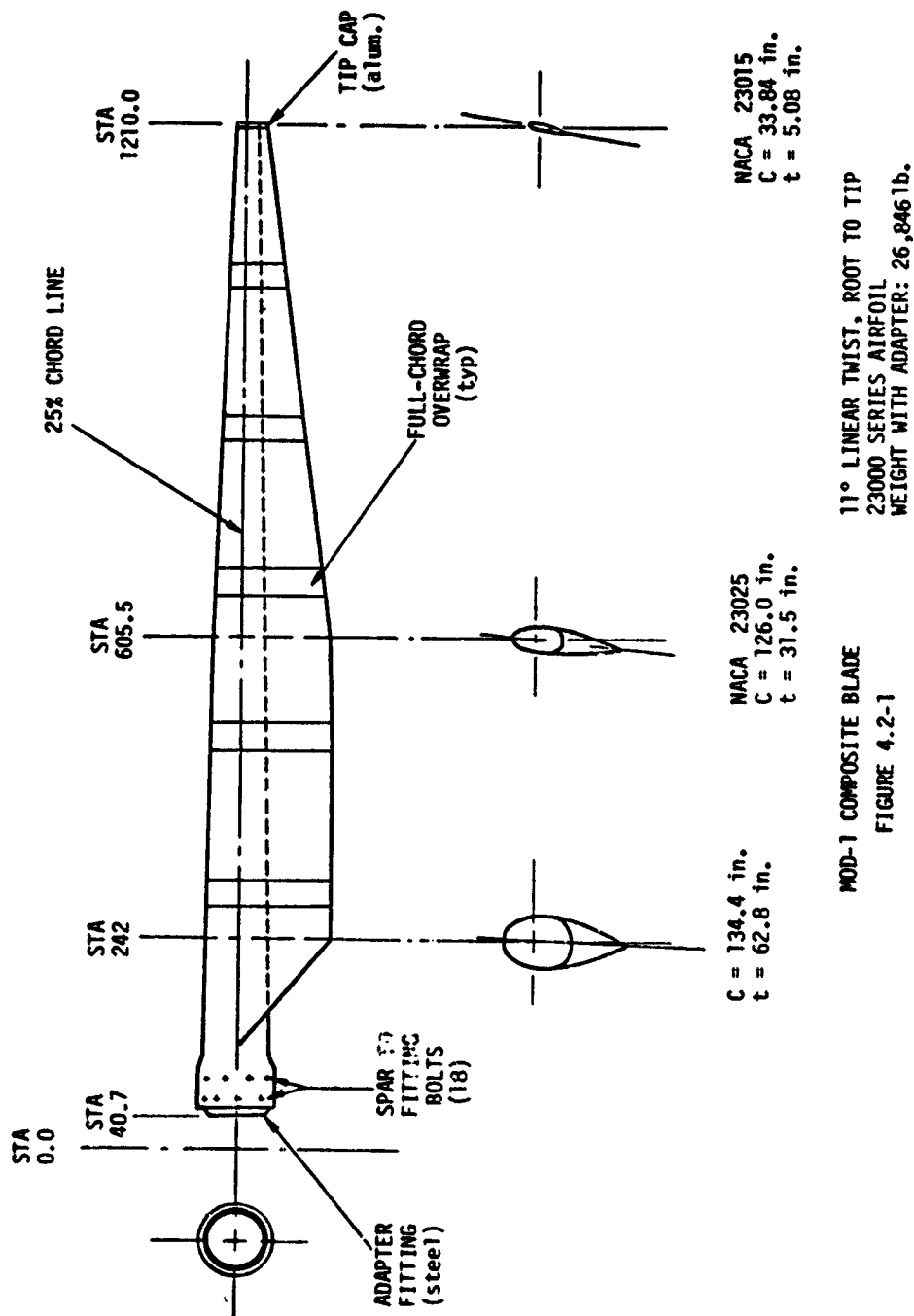


Figure 4.1-9. - Simplified Mod-1 control schematic.

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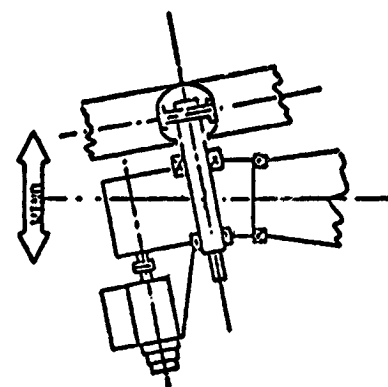
	<u>MOD-1</u>	<u>MOD-1A</u>
WIND REGIME	18 MPH	18 MPH
RATED POWER	2000 kW	2000 kW
LIFE	30 YEARS	30 YEARS
WEIGHT	655,000 LBS	400,000 LBS
2ND UNIT COST ( $\frac{\$}{\text{kW}}$ )	2,900	1,000
COST OF ENERGY ( $\frac{\text{¢}}{\text{kW-HR}}$ )	18	5

\*1978 \$

MCD-1A OBJECTIVES

Figure 4.3-1

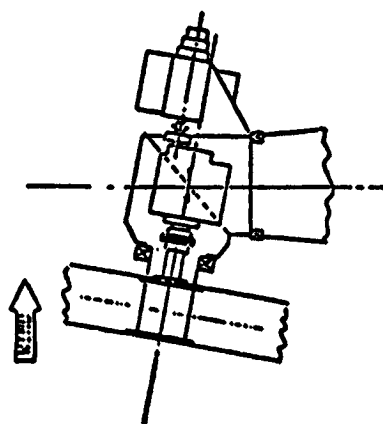
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DESIGN CONCEPT #3  
(INTEGRAL GEARBOX)

- o TEETERED HUB
- o 2 BLADES
- o DOWNWIND OR UPWIND
- o PARTIAL SPAN CONTROL
- o MOD-1 GEAR DRIVE
- o MOD-1 ELEC. GEN.
- o SHELL TOWER (SOFT)

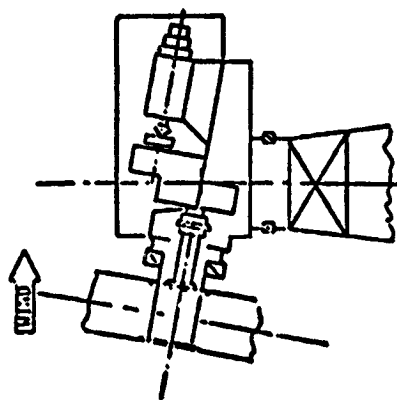
TOTAL WEIGHT  
320,000 LBS



DESIGN CONCEPT #2  
(EPICYCLIC GEAR)

- o FIXED HUB
- o 3 BLADES
- o UPWIND ROTOR
- o PARTIAL SPAN CONTROL
- o EPICYCLIC GEARBOX
- o MOD-1 ELEC. GEN.
- o SHELL TOWER (SOFT)

TOTAL WEIGHT  
355,000 LBS



DESIGN CONCEPT #1  
(REDUCED MOD - 1)

- o FIXED HUB
- o 2 BLADES
- o UPWIND ROTOR
- o PARTIAL SPAN CONTROL
- o MOD-1 GEARBOX
- o MOD-1 ELEC. GEN.
- o TRUSS TOWER (SOFT)

TOTAL WEIGHT  
340,000 LBS

FAVORABLE RESULTS COMPARED  
TO MOD-1 WEIGHT OF 655,000

MOD-1 TRADE-OFF STUDY  
CANDIDATES

Figure 4.3-2

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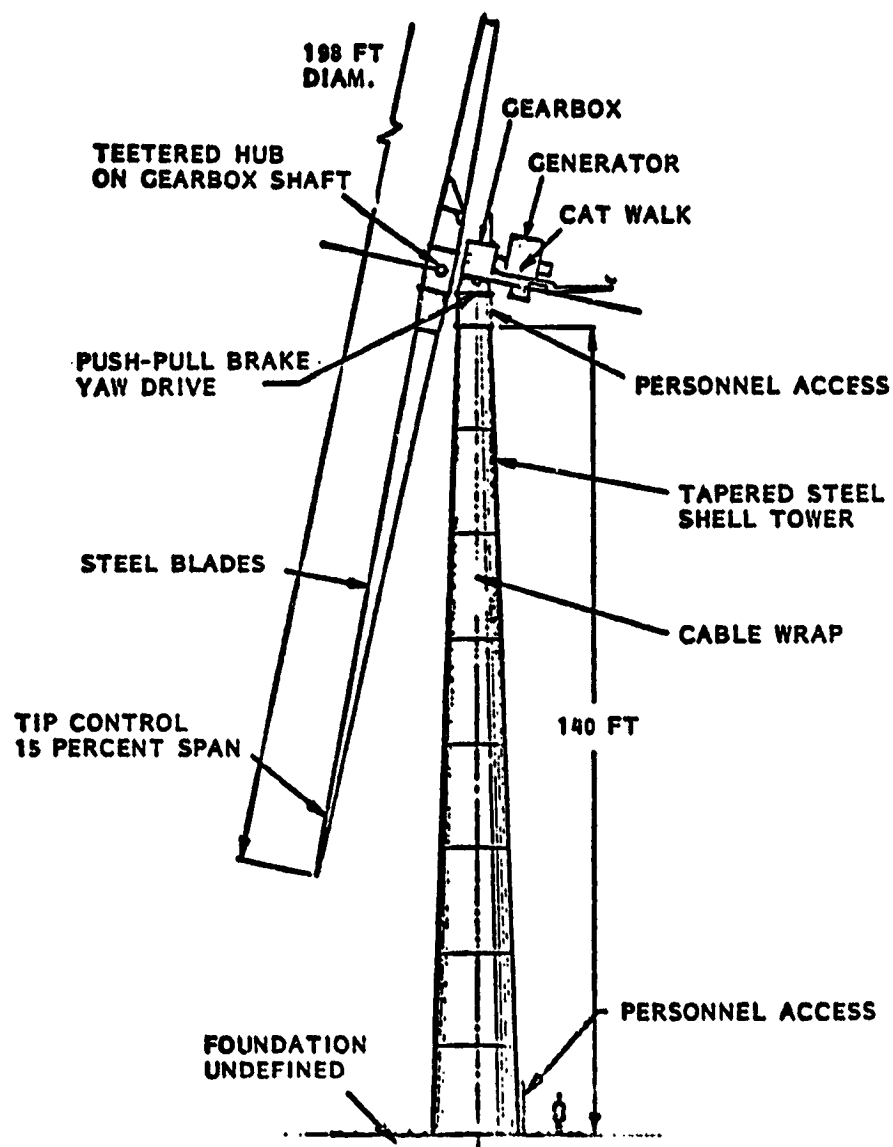


FIGURE 4.3-3 MOD-1A OUTLINE

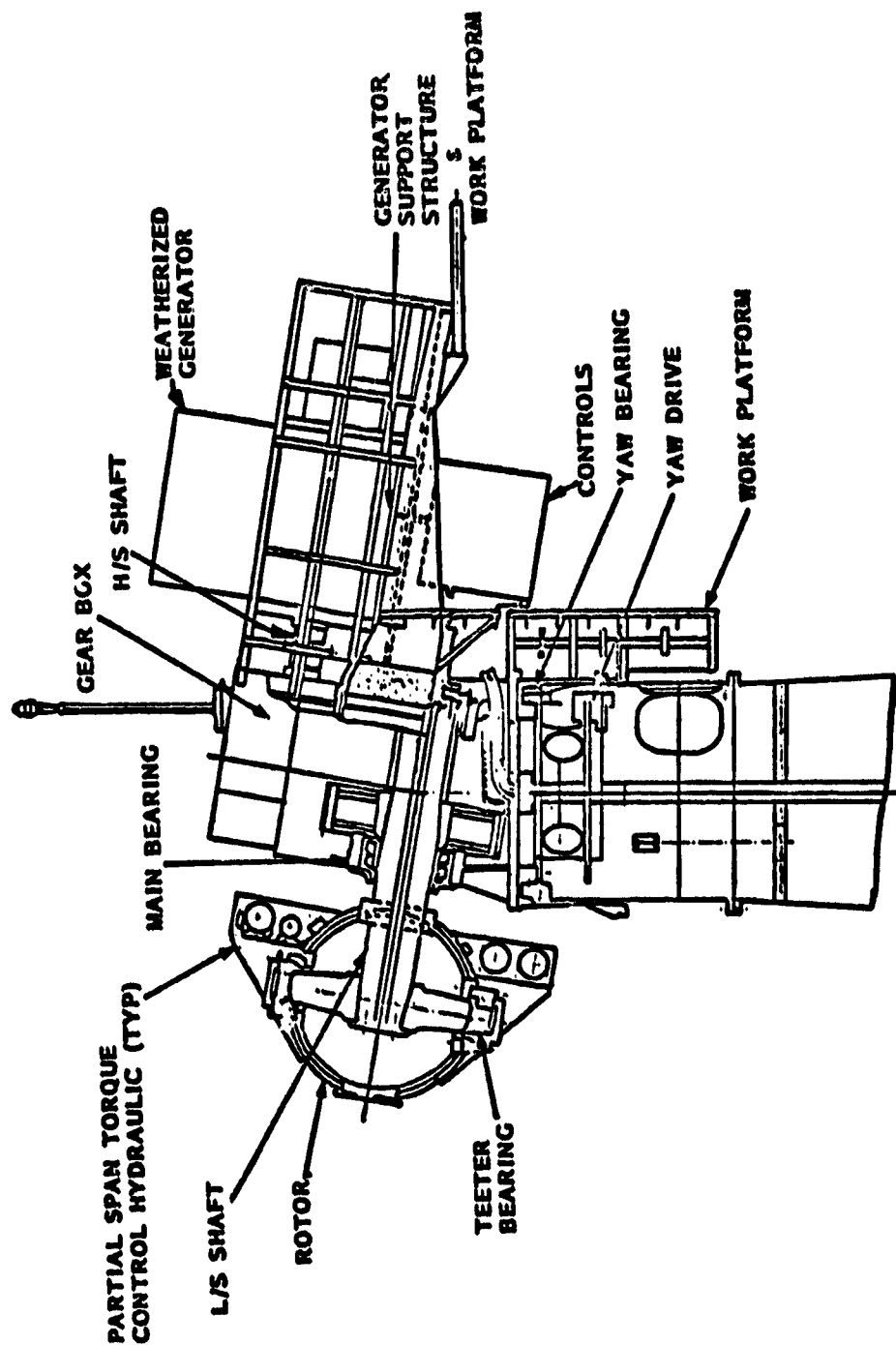
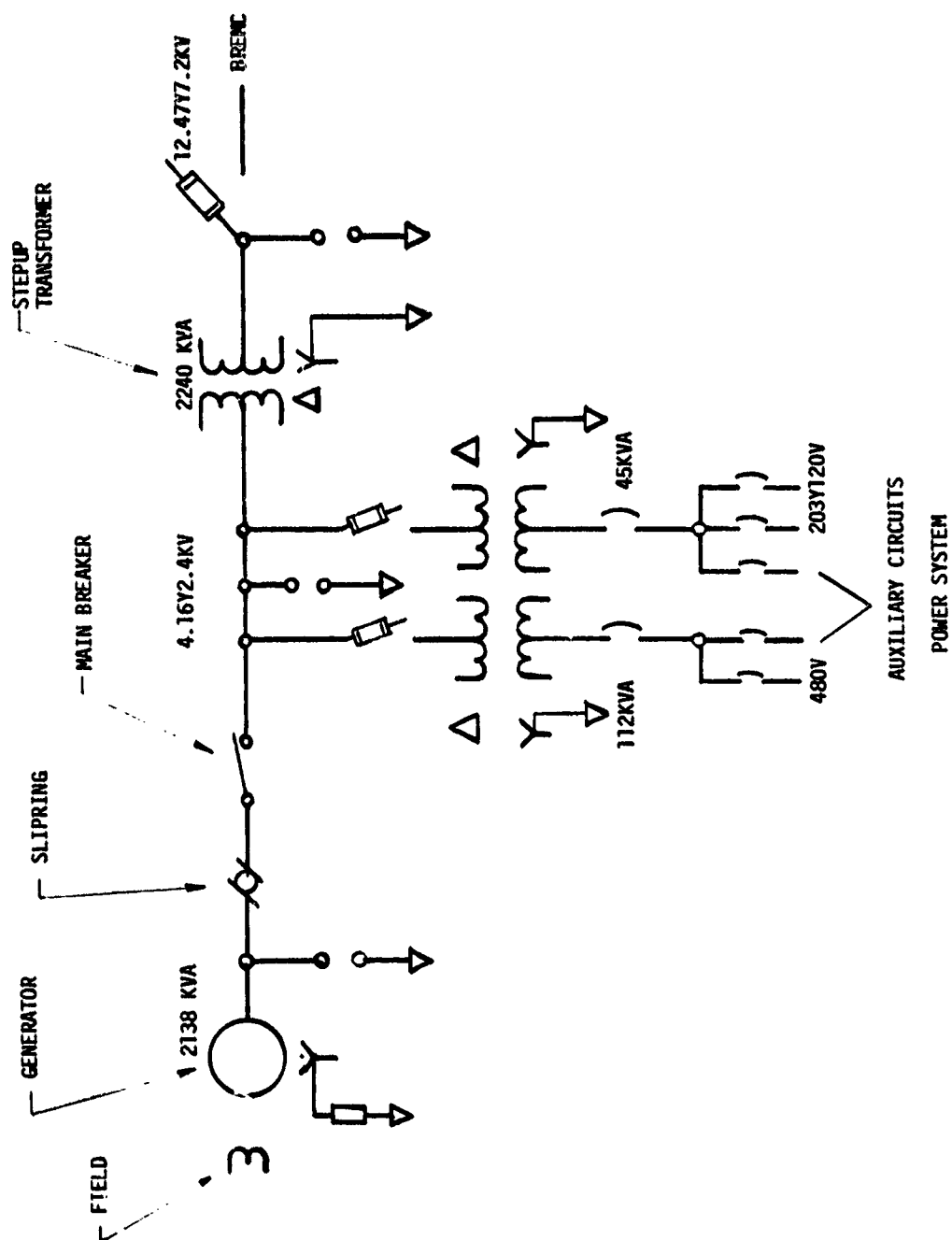


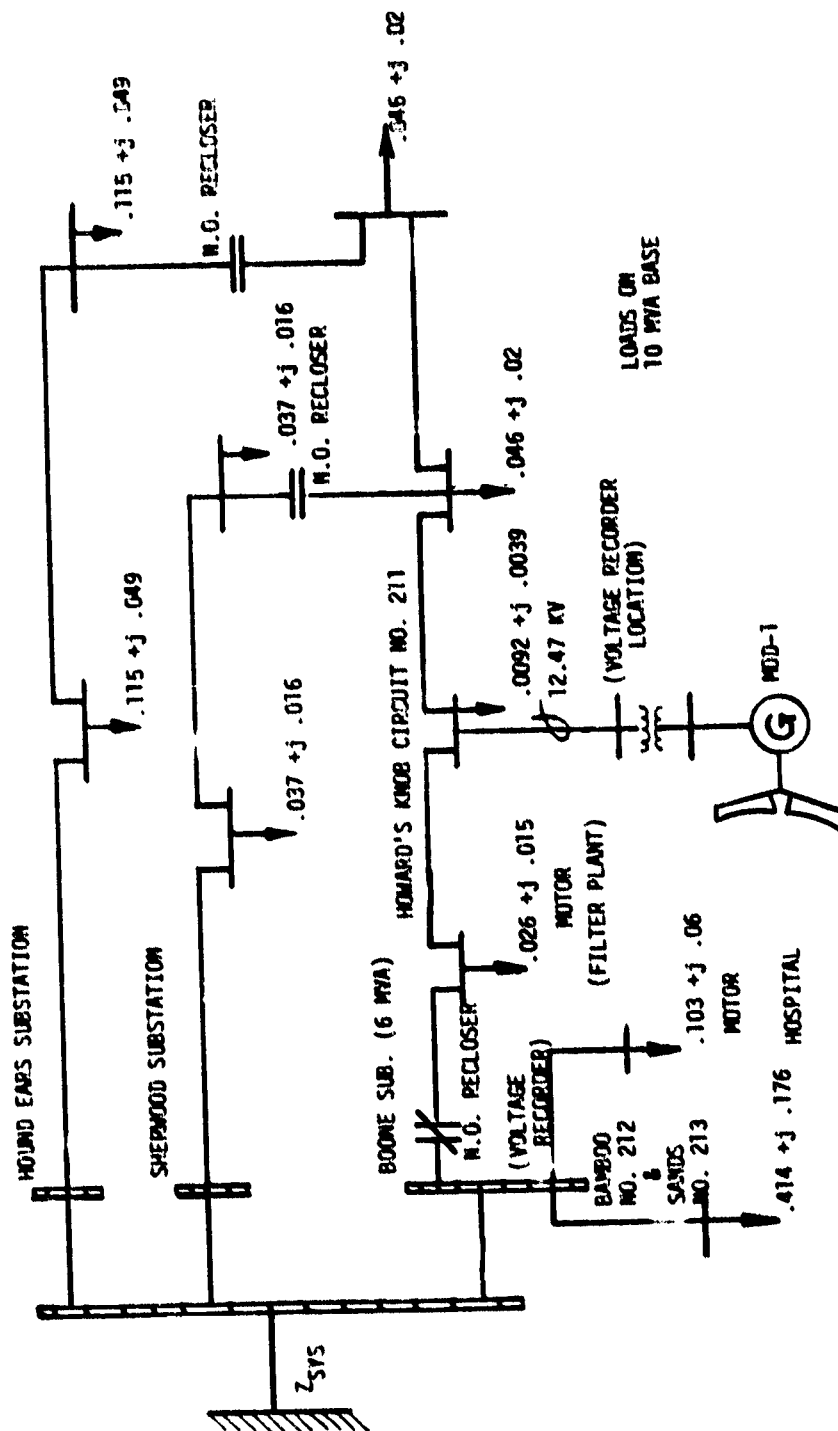
FIGURE 4.3-4 MOD-1A NACELLE

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SIMPLIFIED ONE-LINE DIAGRAM  
Figure 5.1-1

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ONE LINE DIAGRAM OF BREMC DISTRIBUTION SYSTEM

Figure 5.1-2



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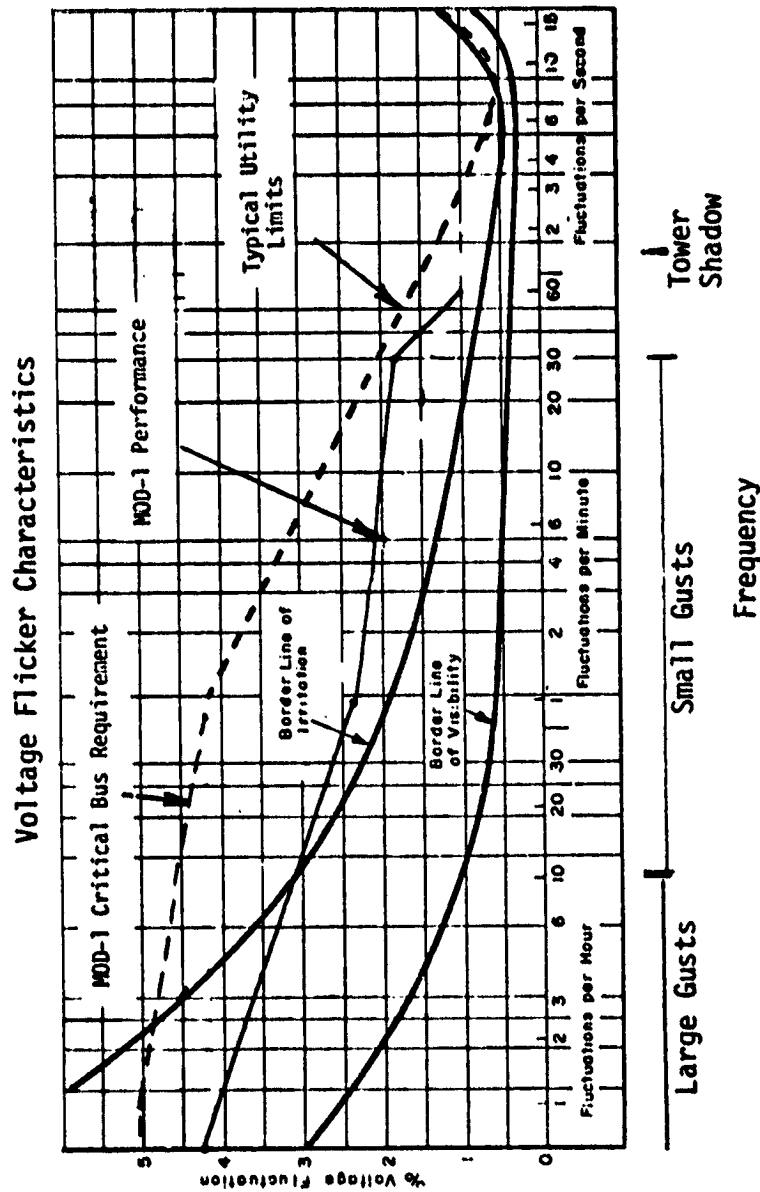
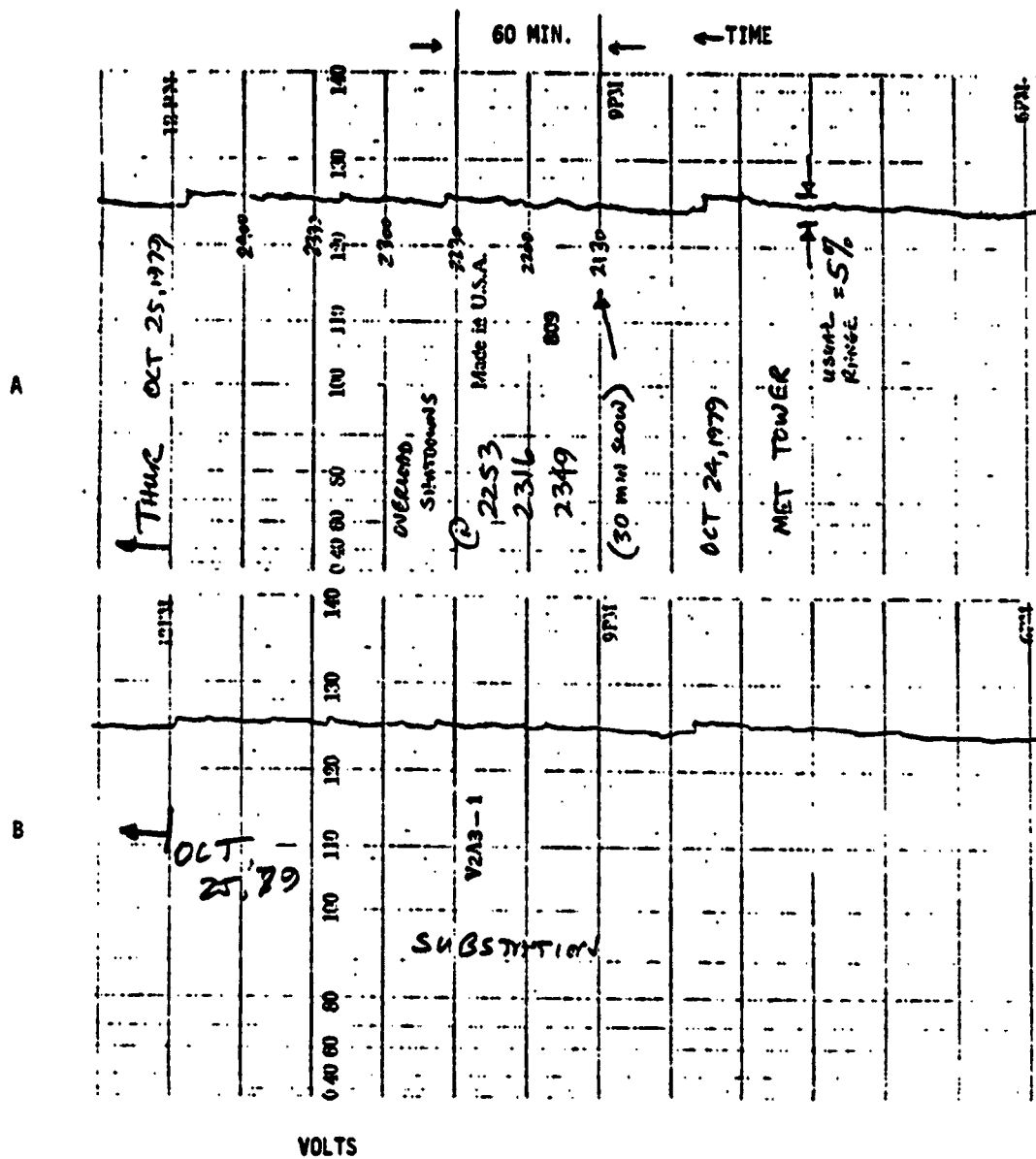


Figure 5.1-3

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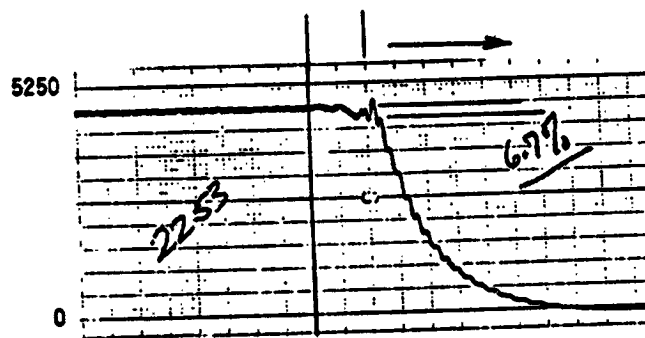


UTILITY VOLTAGE RECORDER TRACES  
OCTOBER 24, 1979

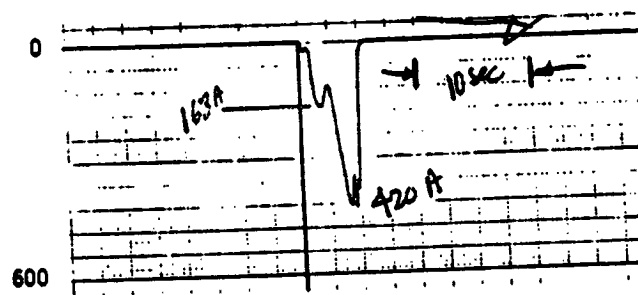
Figures 5.1-4a and 5.1-4b

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LINE-LINE  
VOLTAGE  
AT GENERATOR



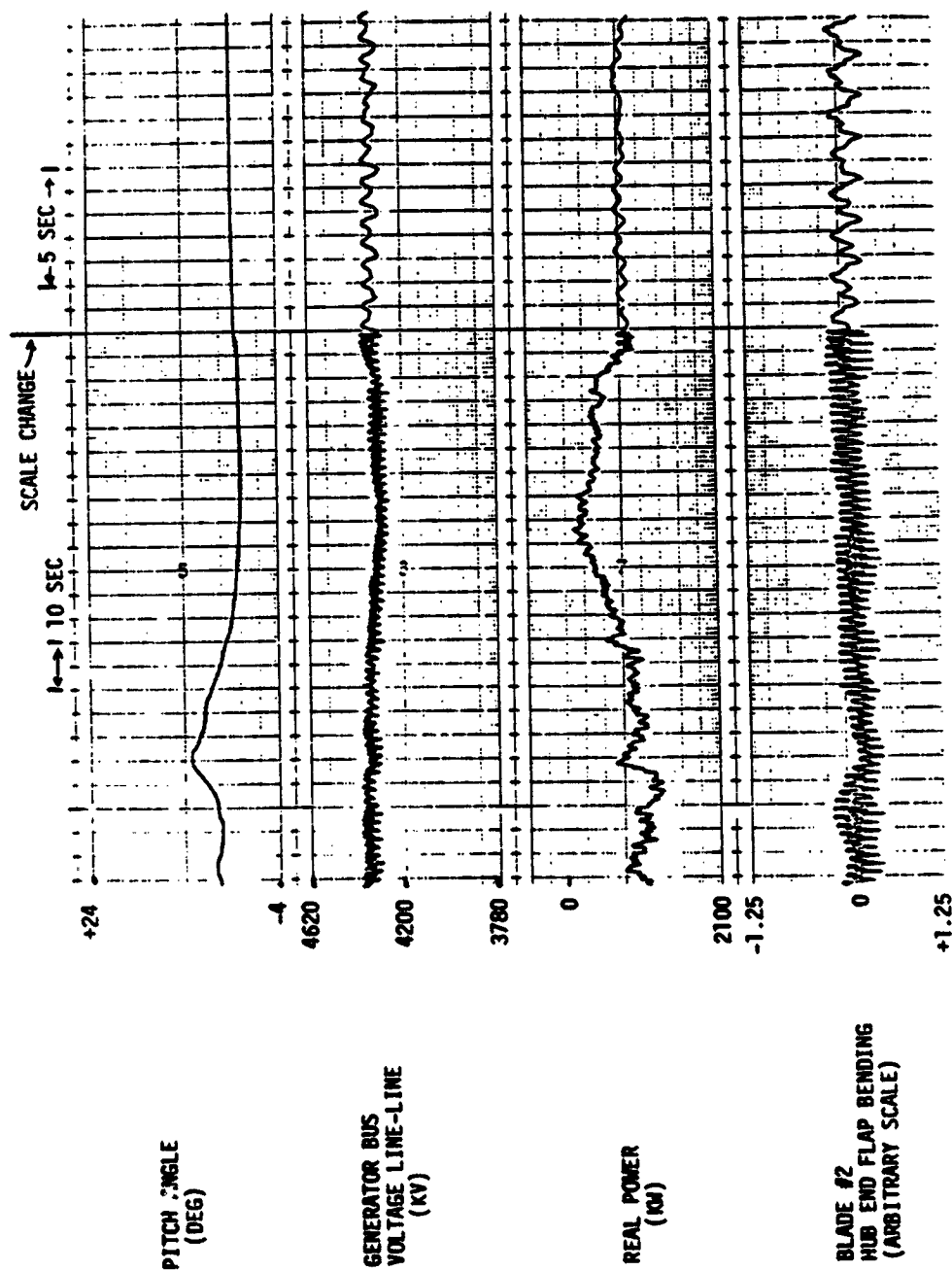
PHASE  
CURRENT  
AT 4.16 KV



TRANSIENT ON OCTOBER 24, 1979

Figure 5.1-4c

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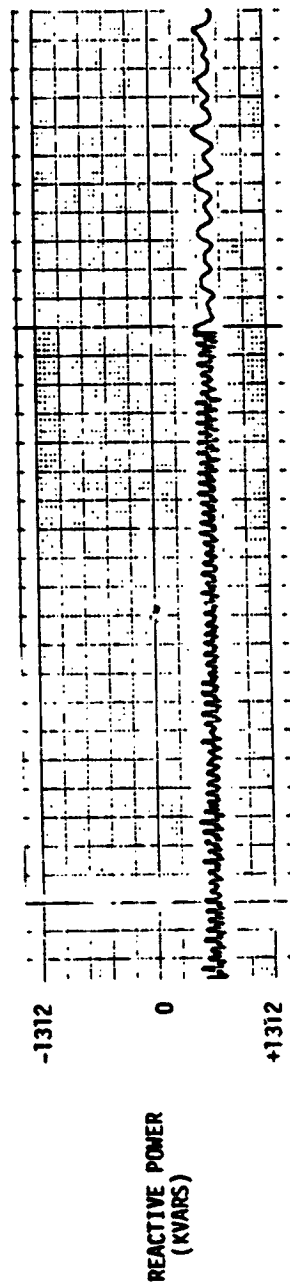


MOD-1 OPERATION AT 34.7 RPM

JANUARY 31, 1980

Figure 5.1-5a

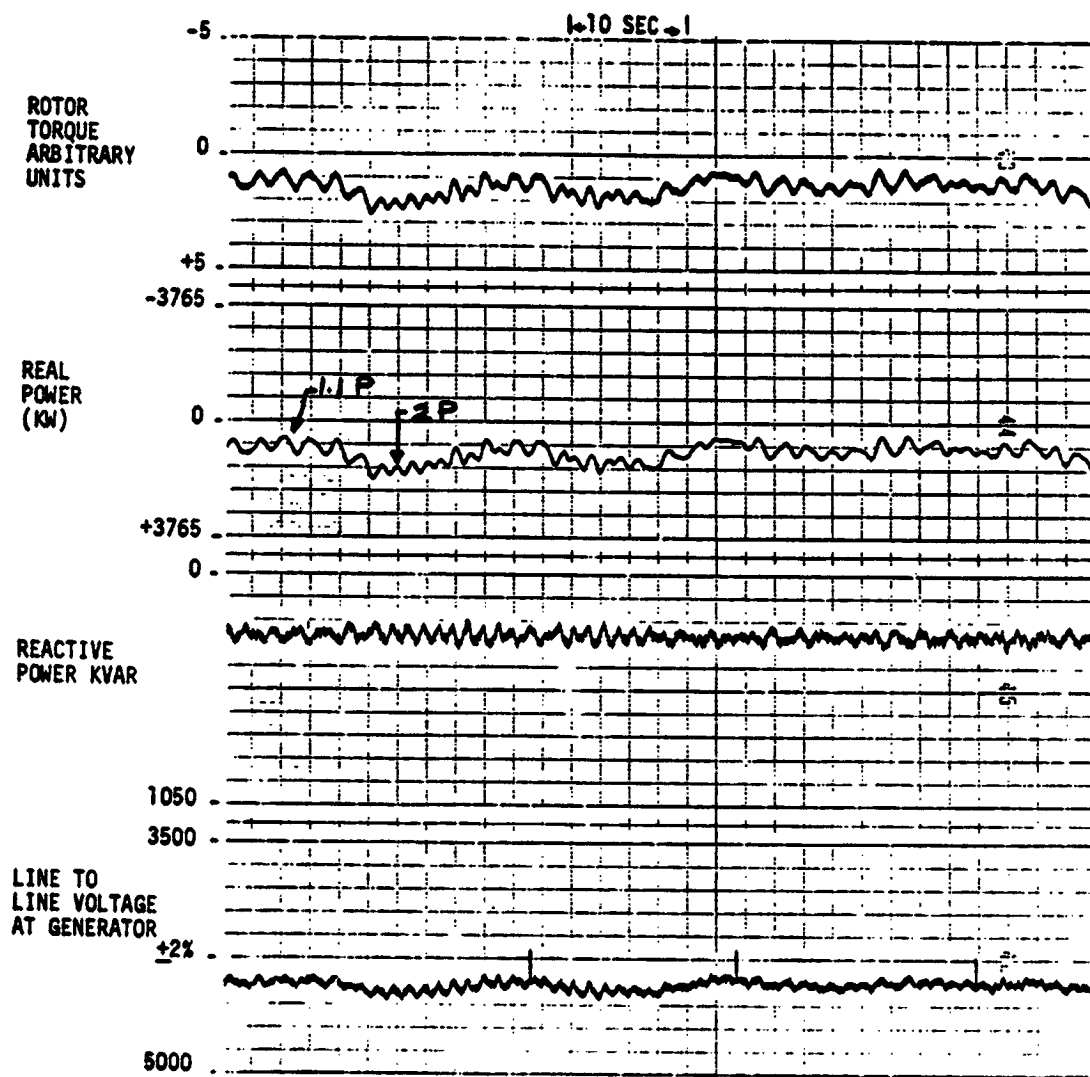
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MOD-1 OPERATION AT 34.7 RPM  
JANUARY 31, 1980

Figure 5.1-5b

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TYPICAL 23 RPM OPERATION  
JANUARY 19, 1981, 0816 HRS

Figure 5.1-6

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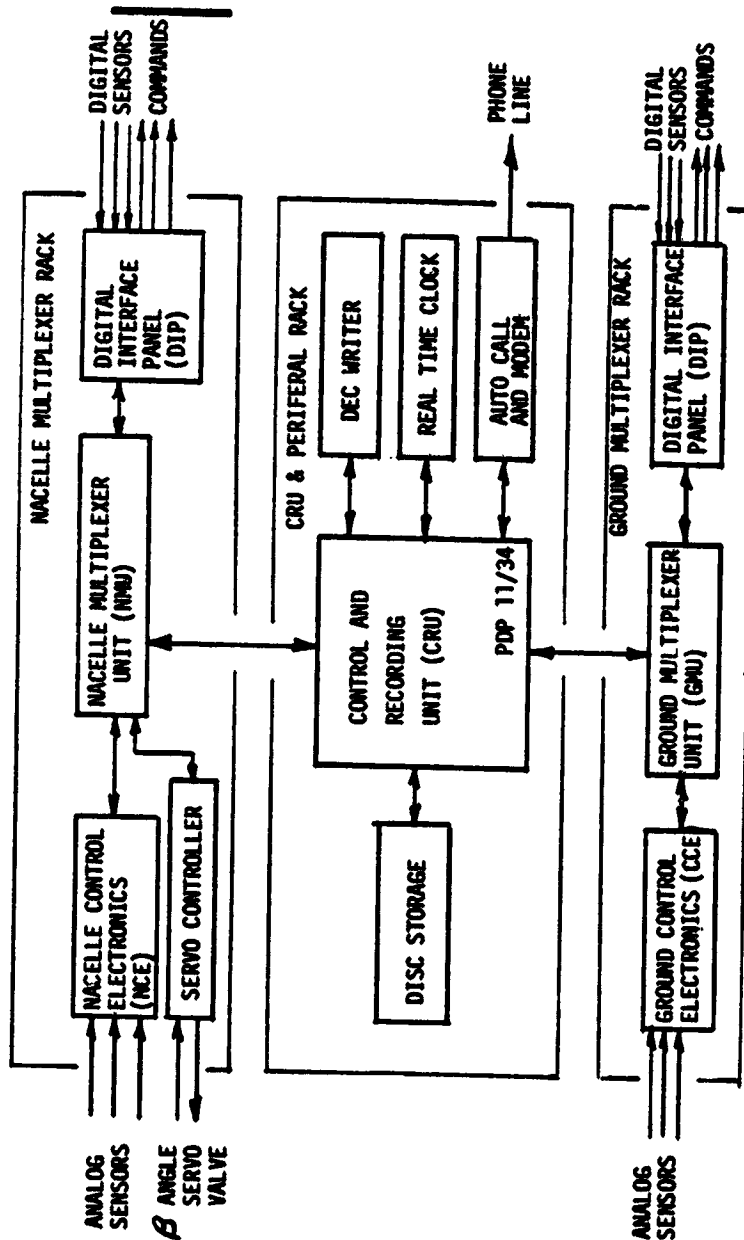


Figure 5.2-1. Control Subsystems Block Diagram

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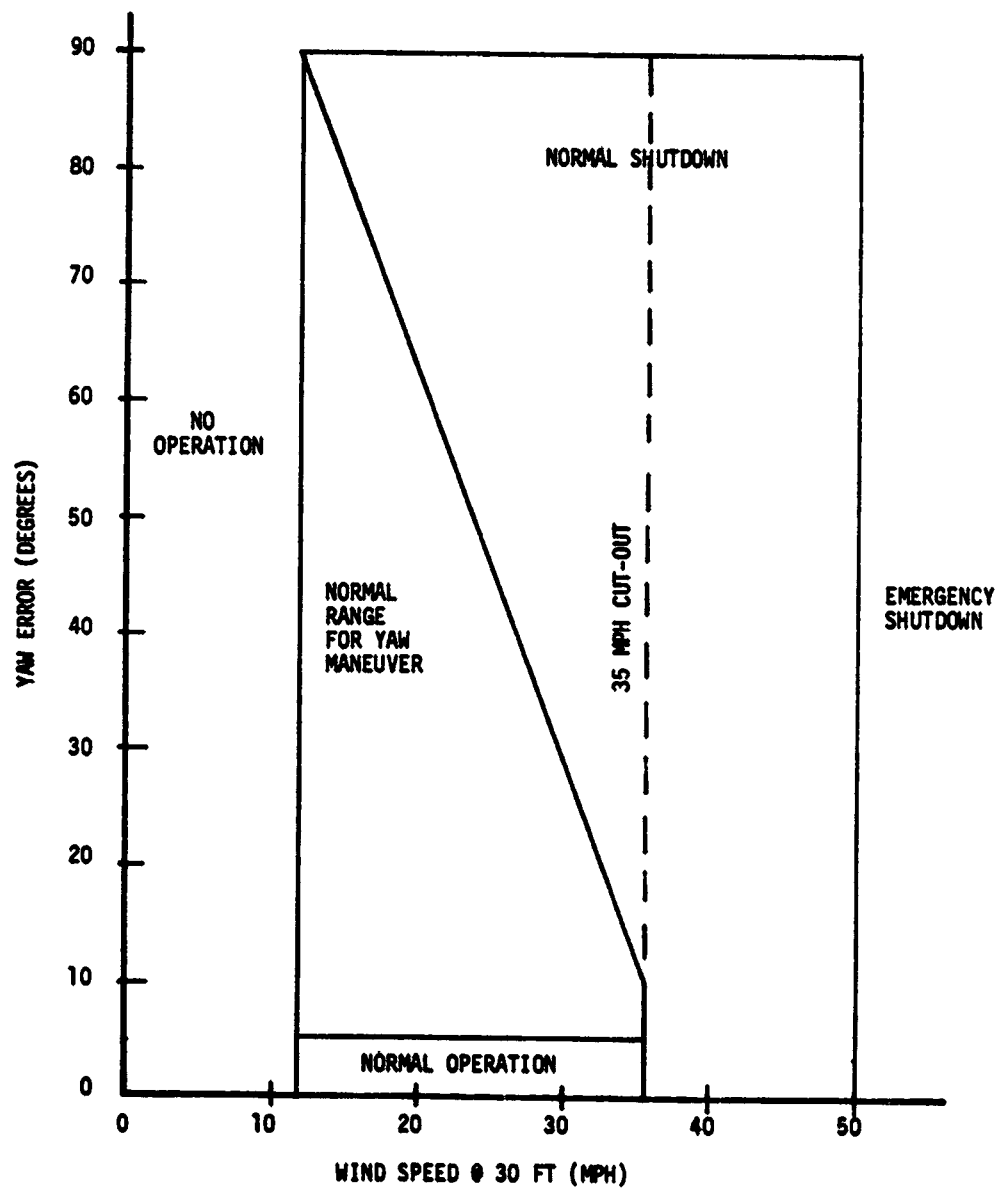


Figure 5.2-2. MDD-1 Operational Envelope



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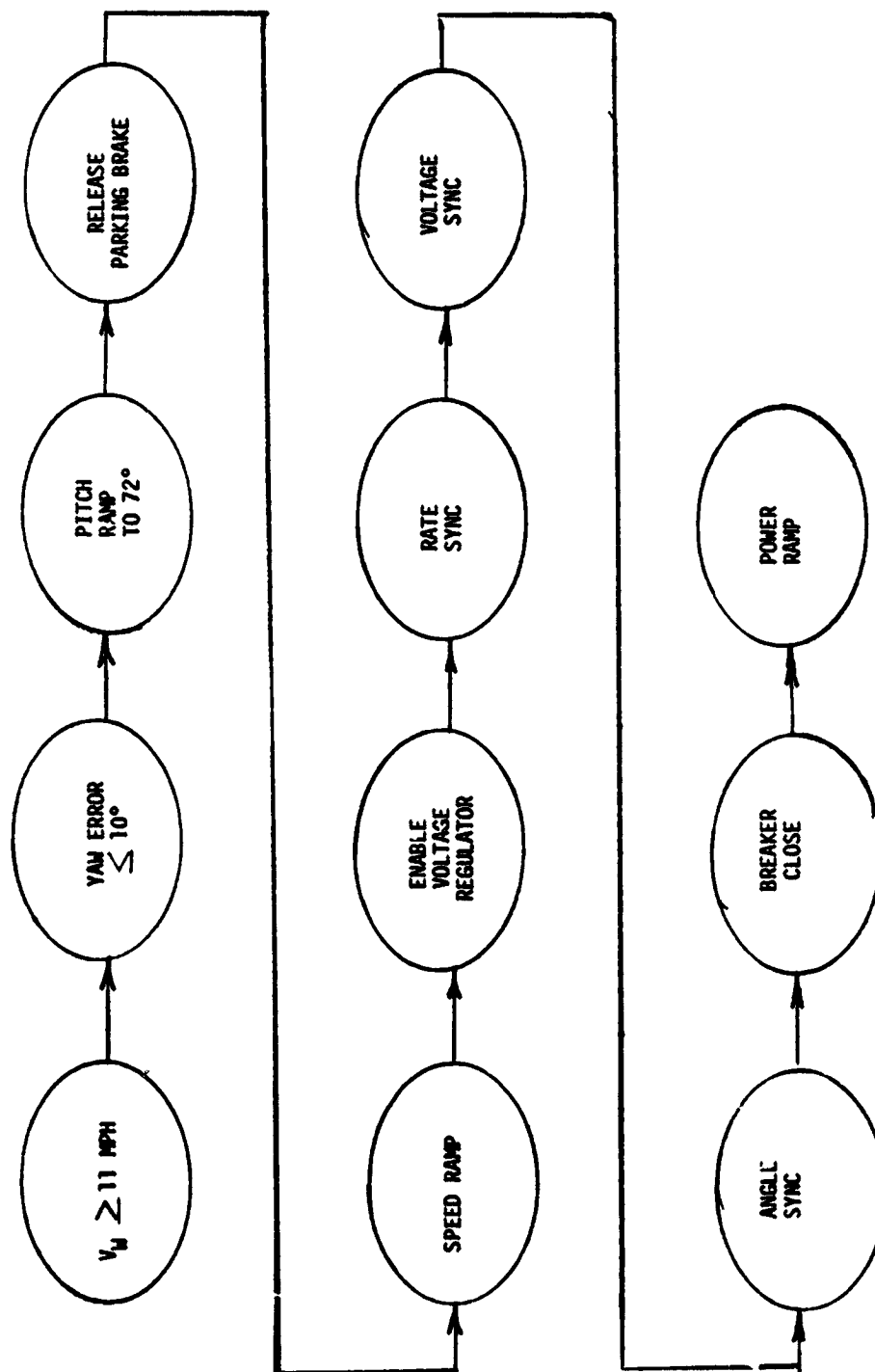


Figure 5.2-3. Startup Control Functions

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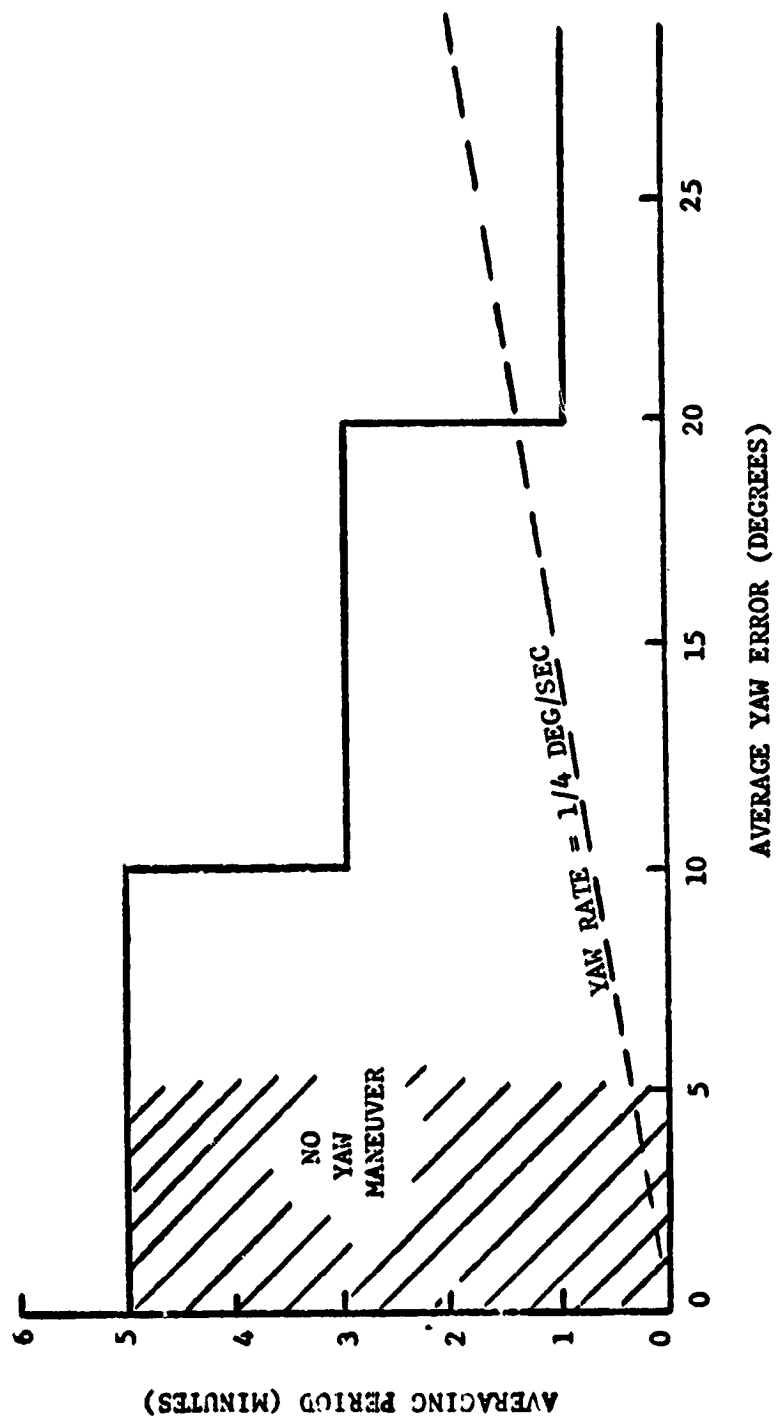


Figure 5.2-4. Yaw Correction Averaging Logic

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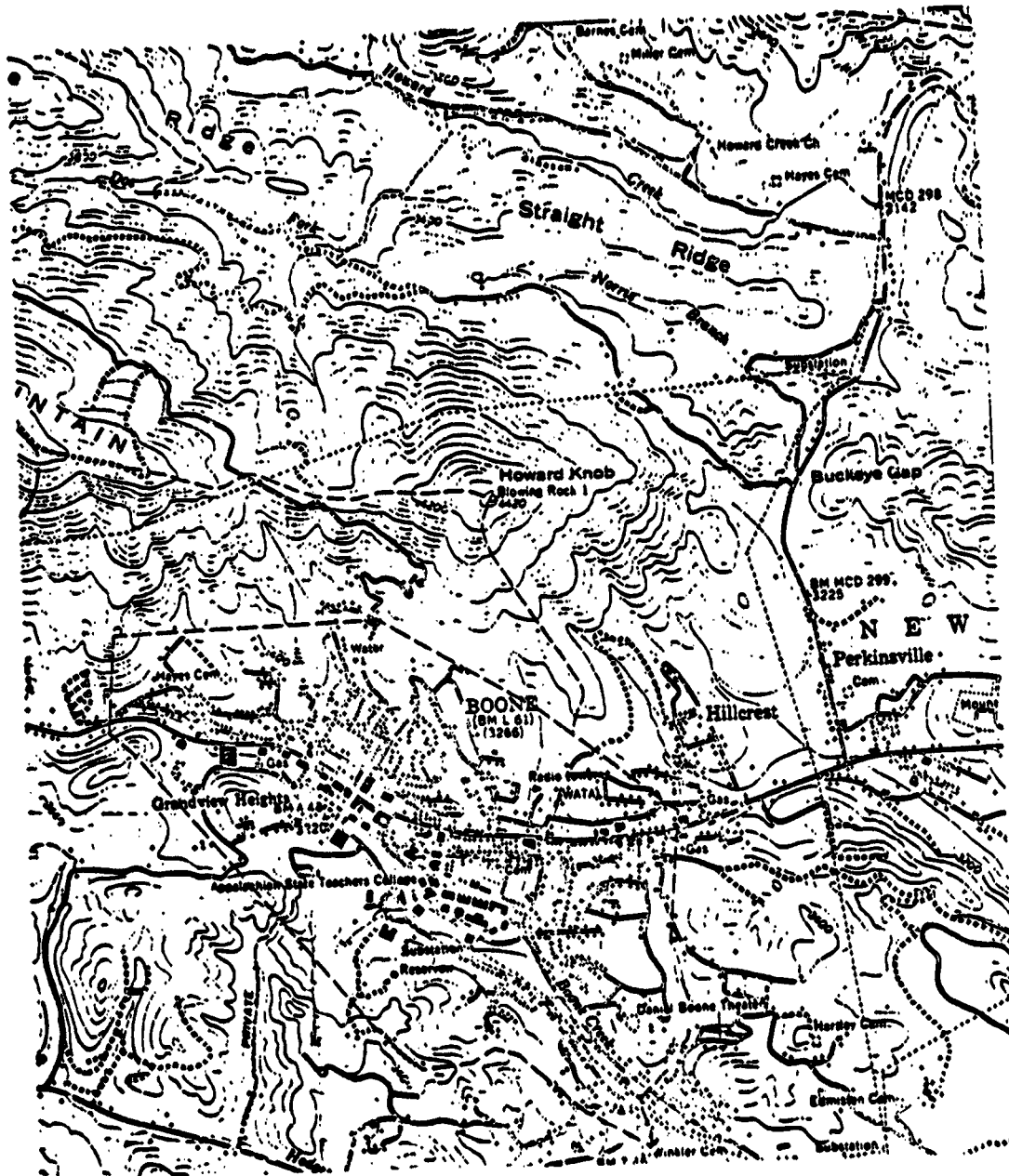


FIGURE 5.3-1: Topographical map of the Boone area

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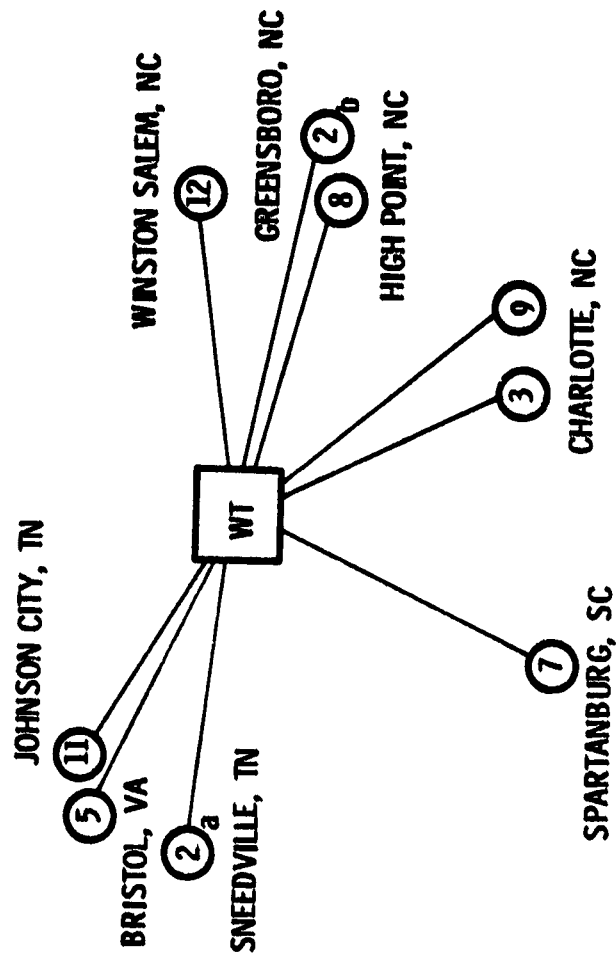


Figure 5.3.1-1. - TV stations received in Boone.

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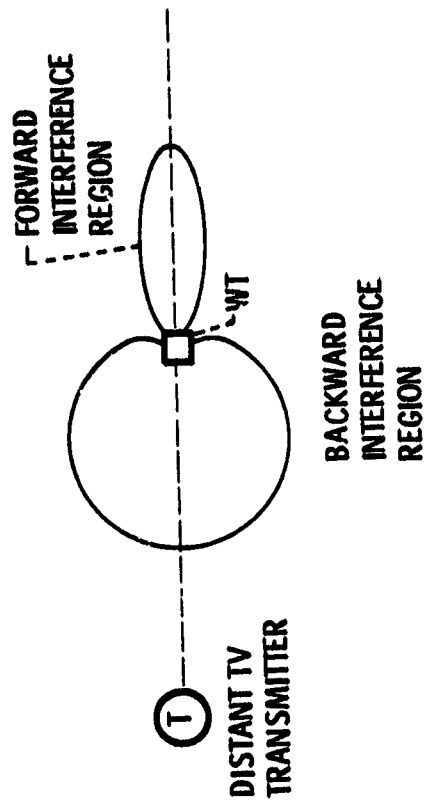


Figure 5.3.1-2. - Television forward and backward interference regions for a wind turbine.

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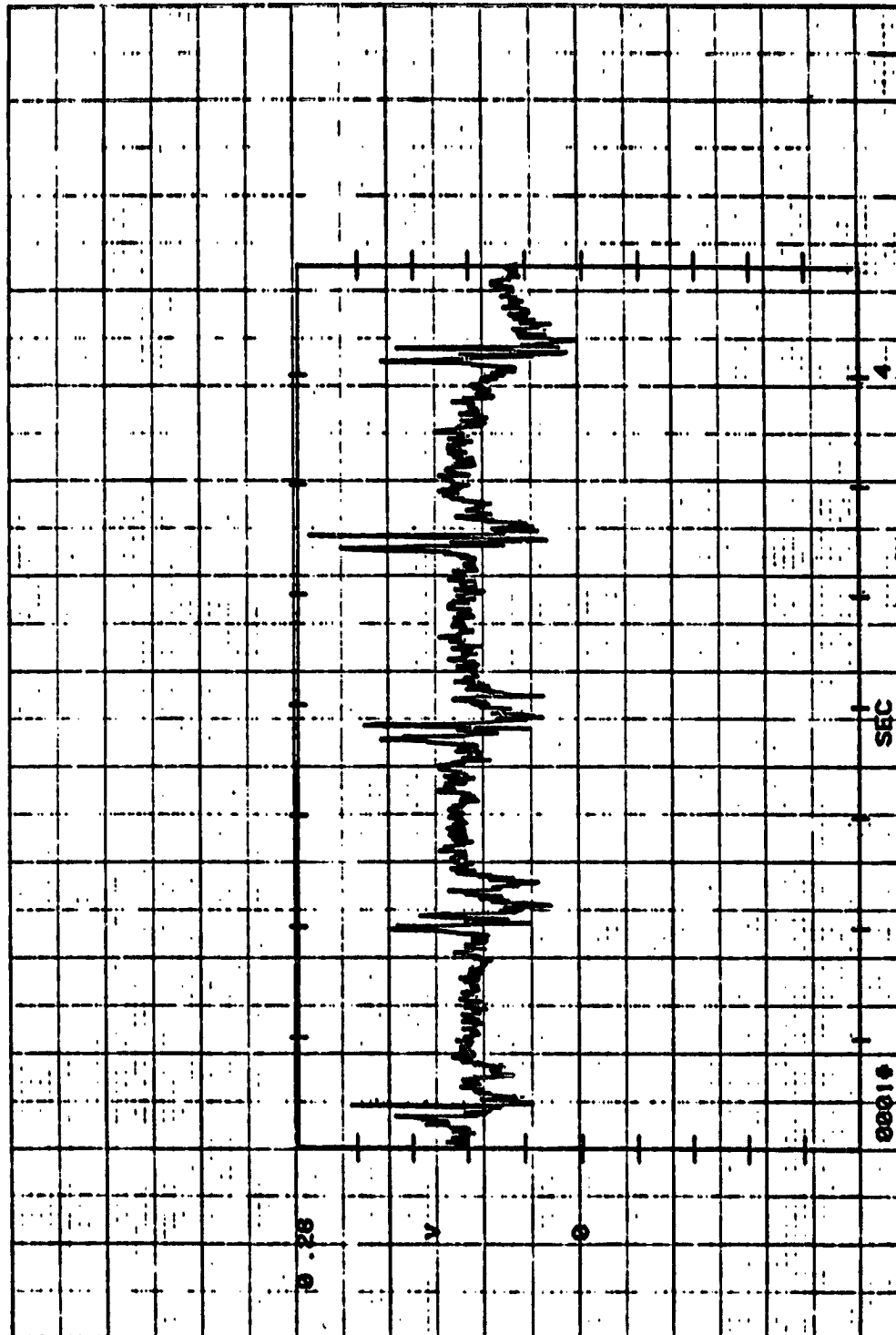


FIGURE 5.3.2-1 Impulse Sequence Near Machine, 35 rpm, 500 KV, April 1, 1980

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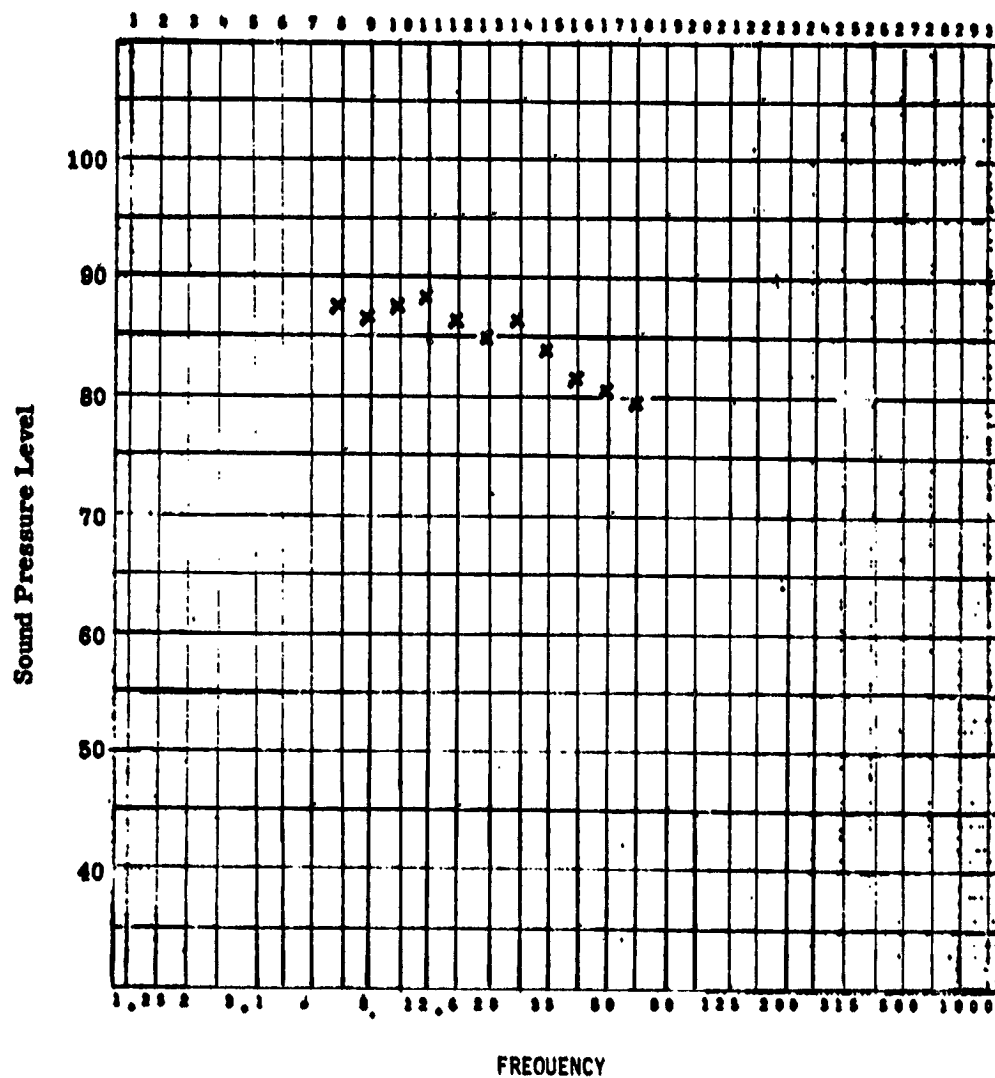


Figure 5.3.2-2. Sound Pressure Levels  
1000 KW 50' From WT  
February 12, 1980

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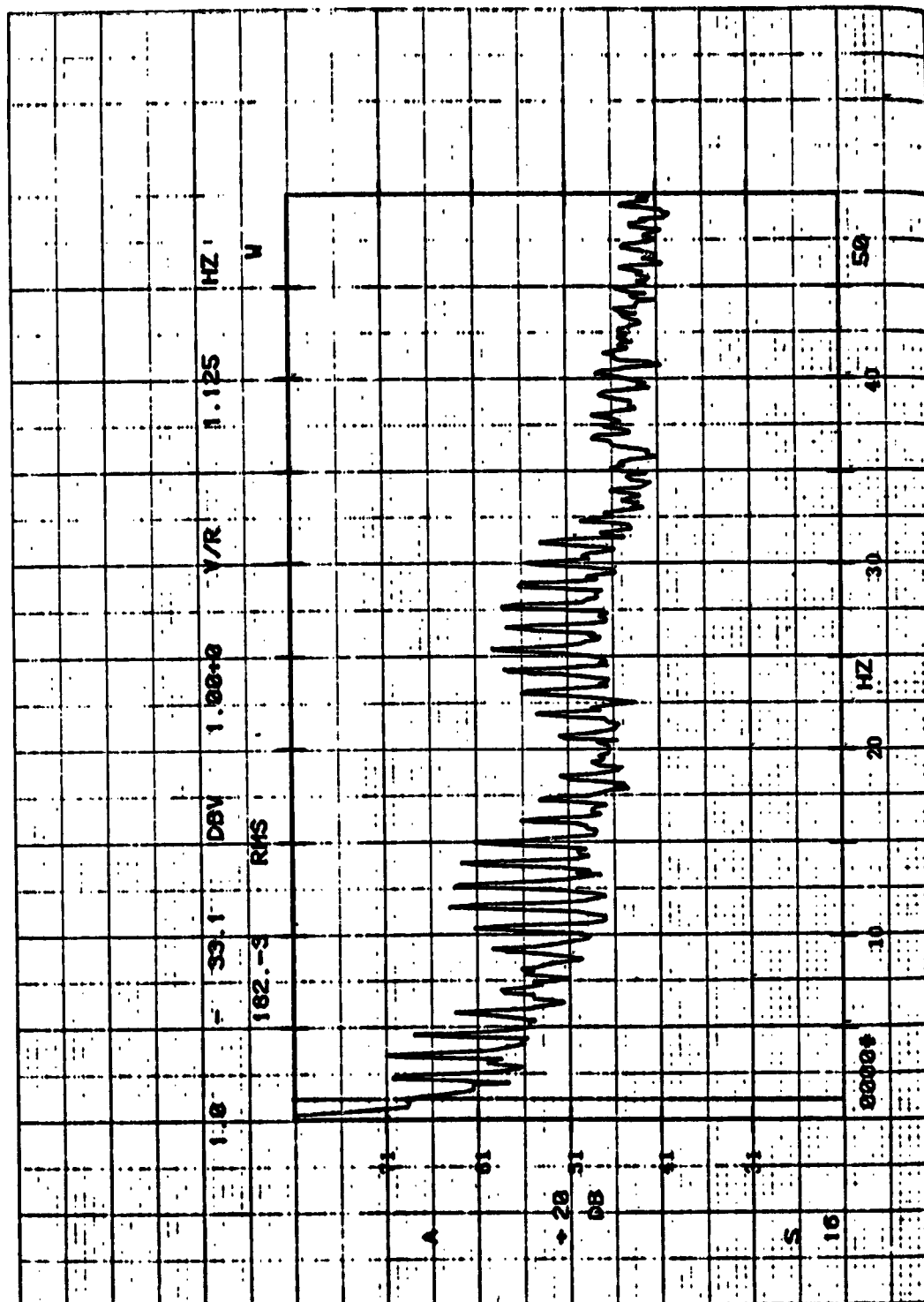


Figure 5.3.2-3. Sound Pressure Levels Versus Frequency Outside Residence  
12:07 P.M., March 31, 1980



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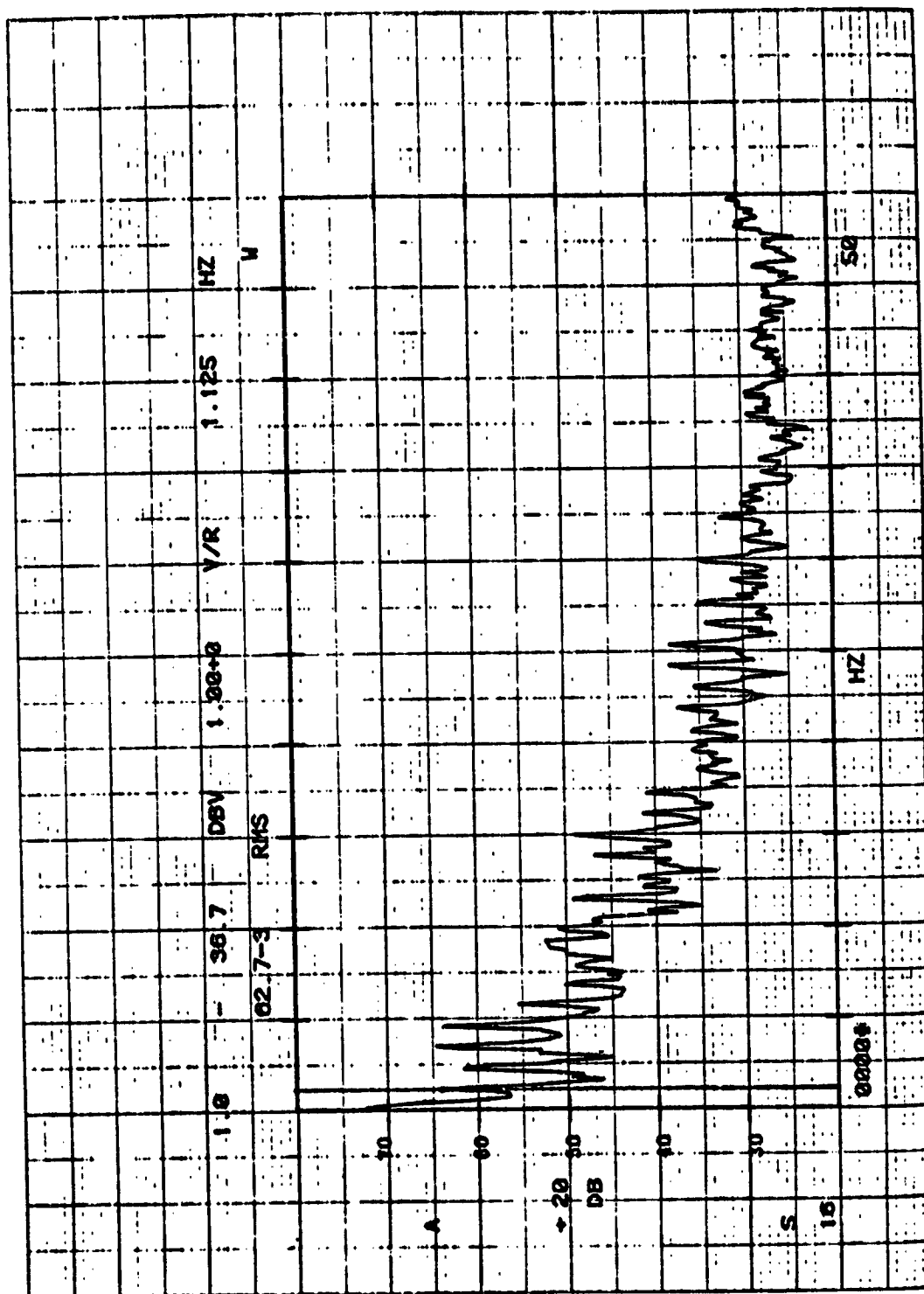
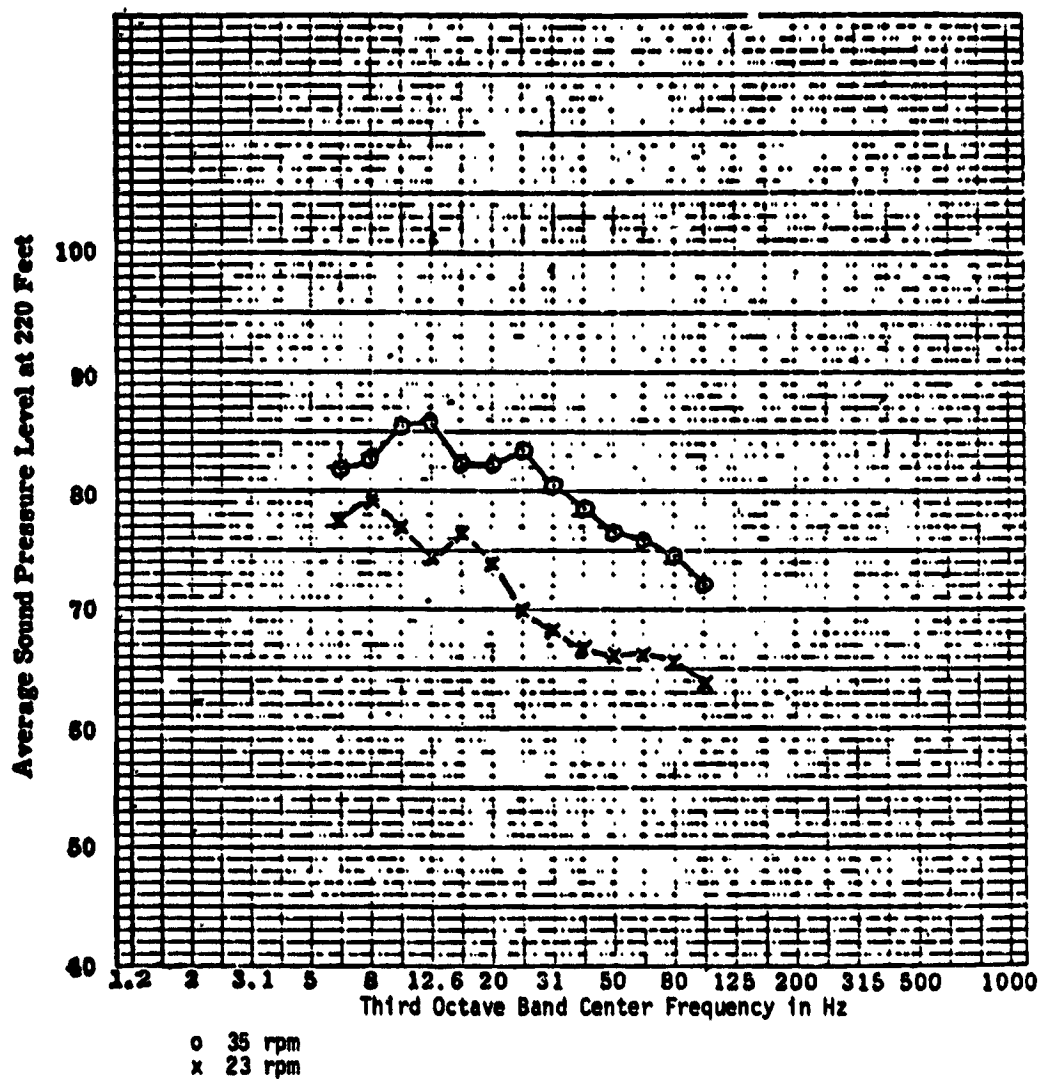


Figure 5.3.2-4. Sound Pressure Level Versus Frequency Inside Residence  
12:07 A.M., March 31, 1980

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Each curve represents average sound pressure levels for seven sets of data -- with different but comparable wind conditions and load.

Figure 5.2.2-5. Average Sound Pressure at 35 and 23 RPM

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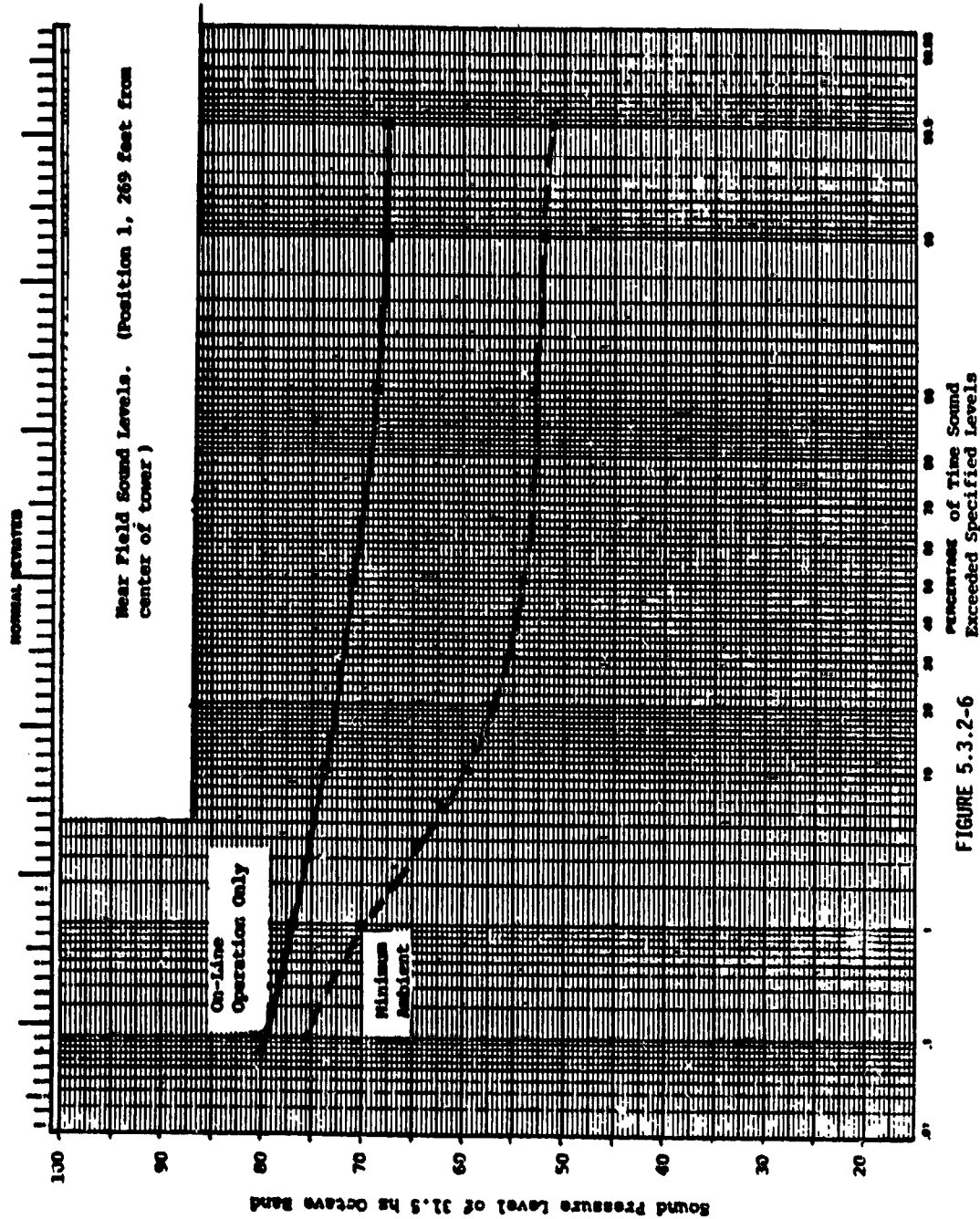


FIGURE 5.3.2-6

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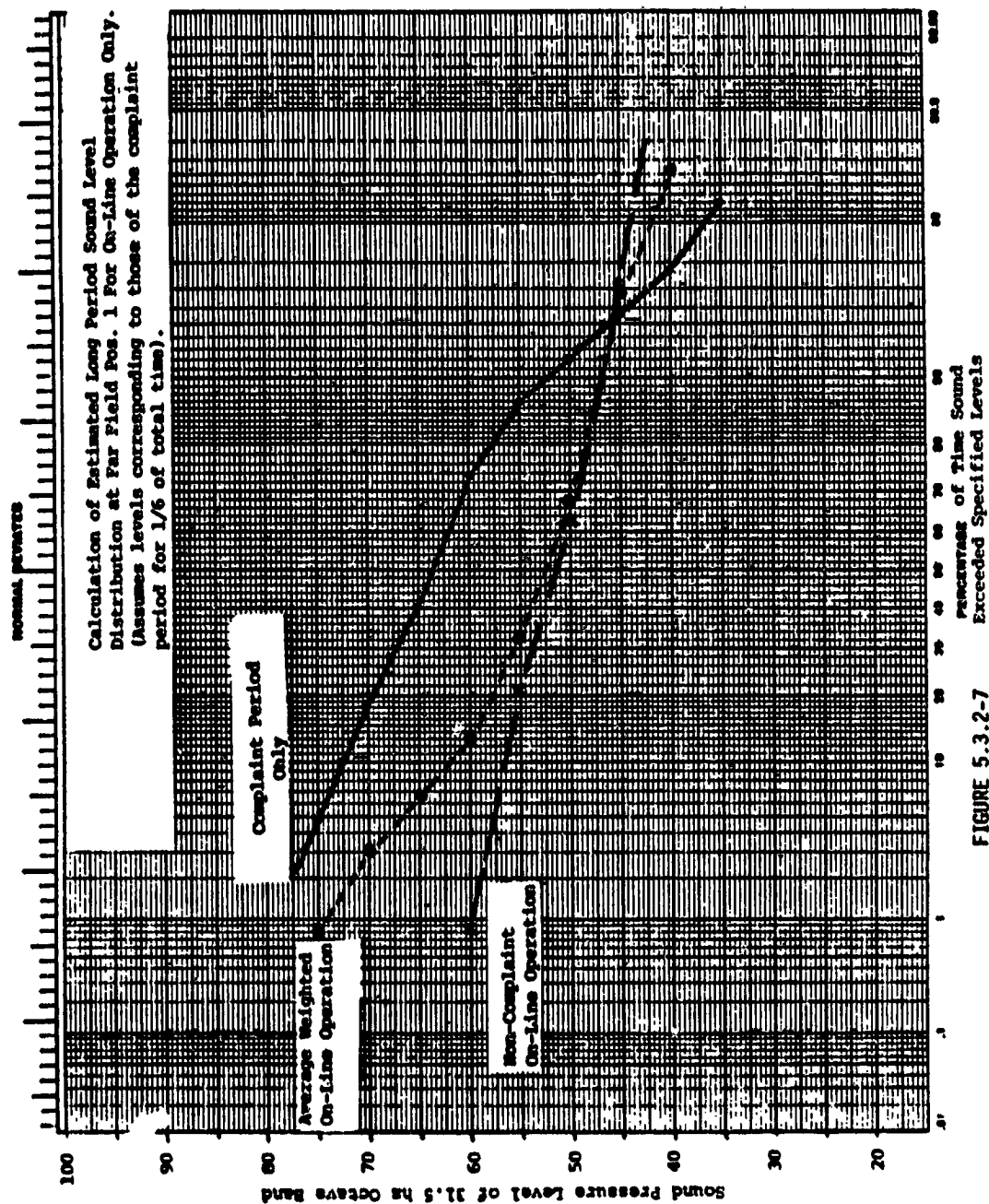


FIGURE 5.3.2-7

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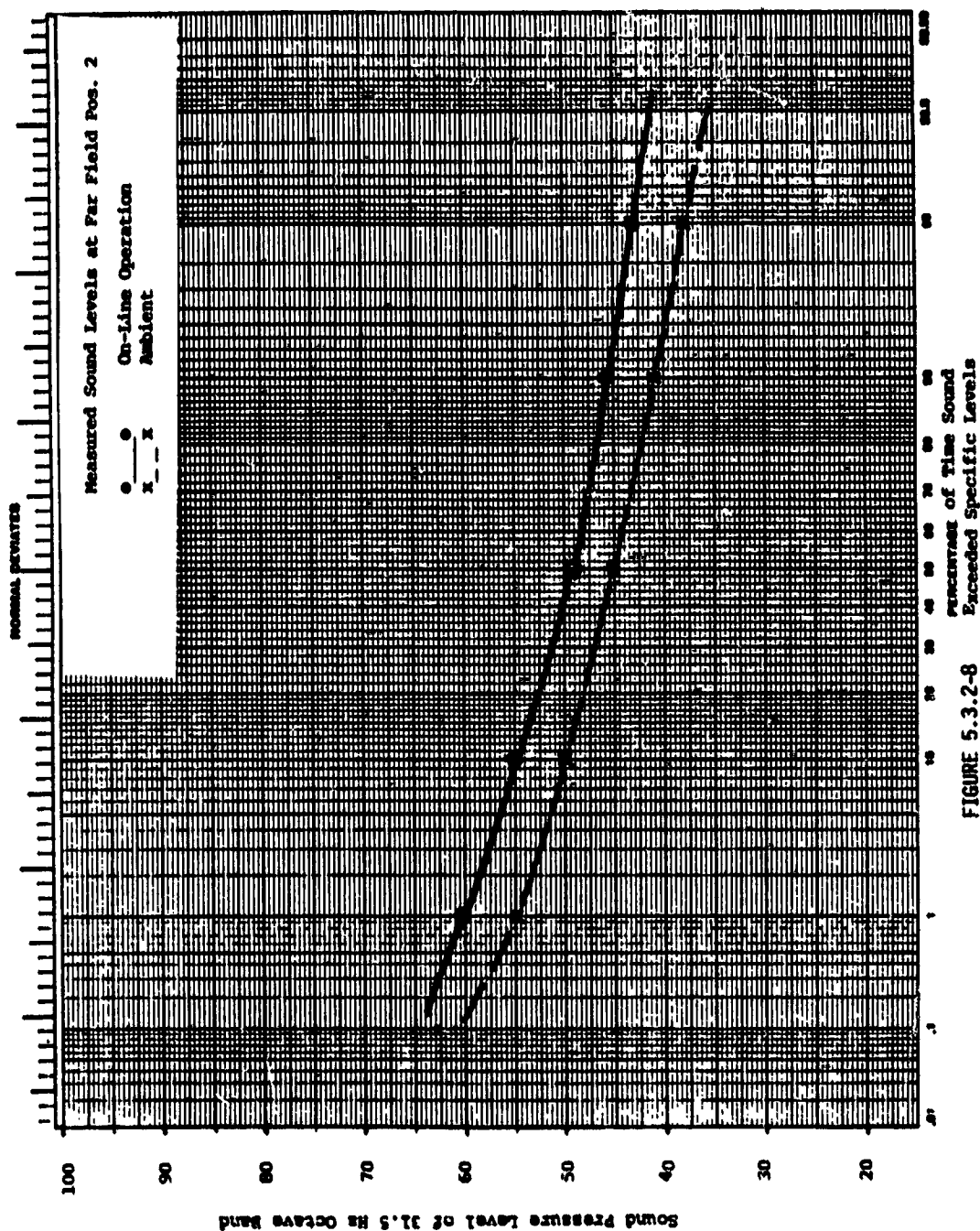


FIGURE 5.3.2-8

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OUTPUT POWER OF THE MOD-1 2-MW WIND ENERGY SYSTEM  
60 M ROTOR STEEL BLADES BOONE, NC

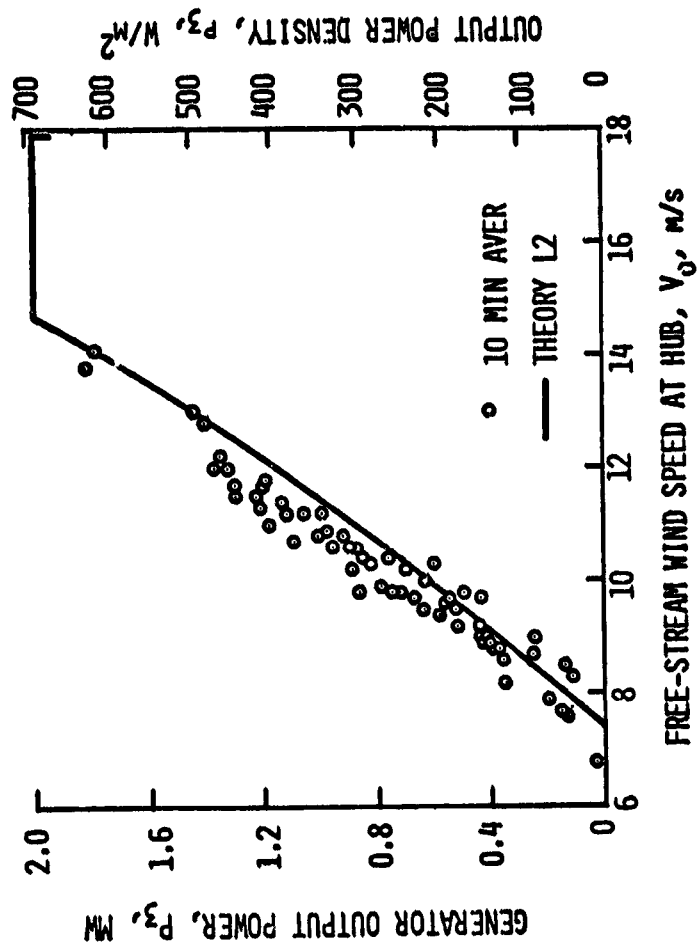


Figure 5.4-1

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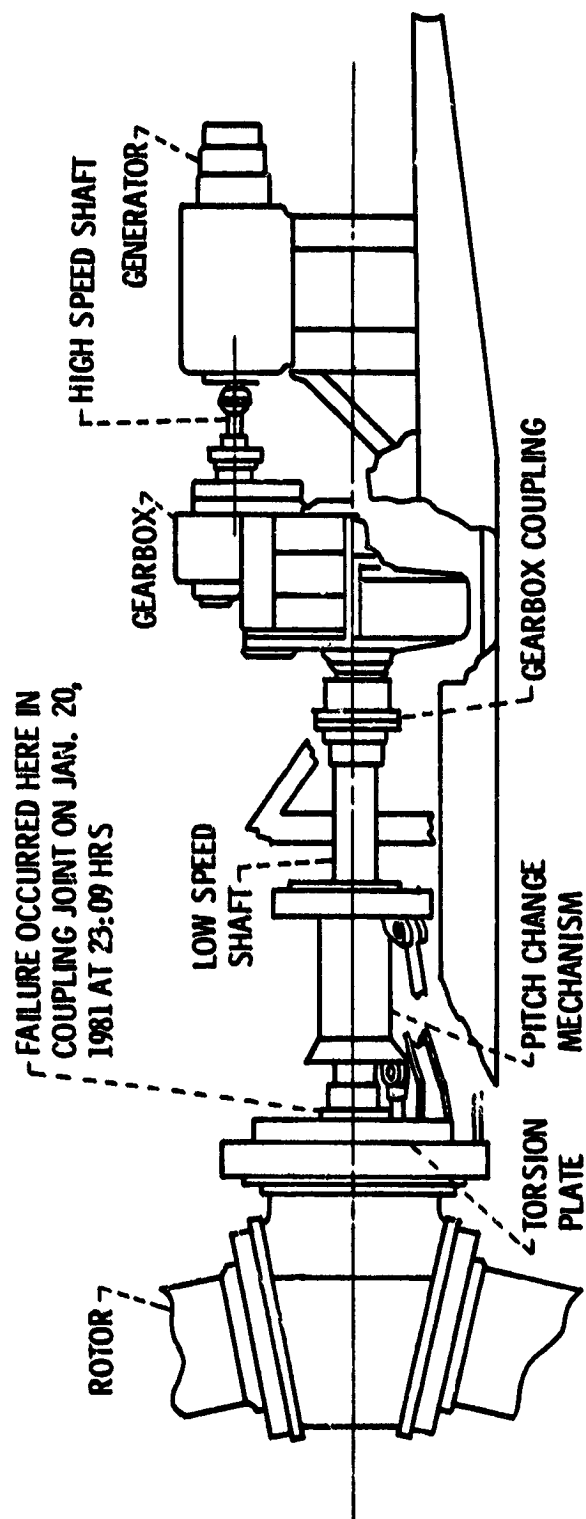


Figure 5.5.2-1. - Mod 1 drive train.

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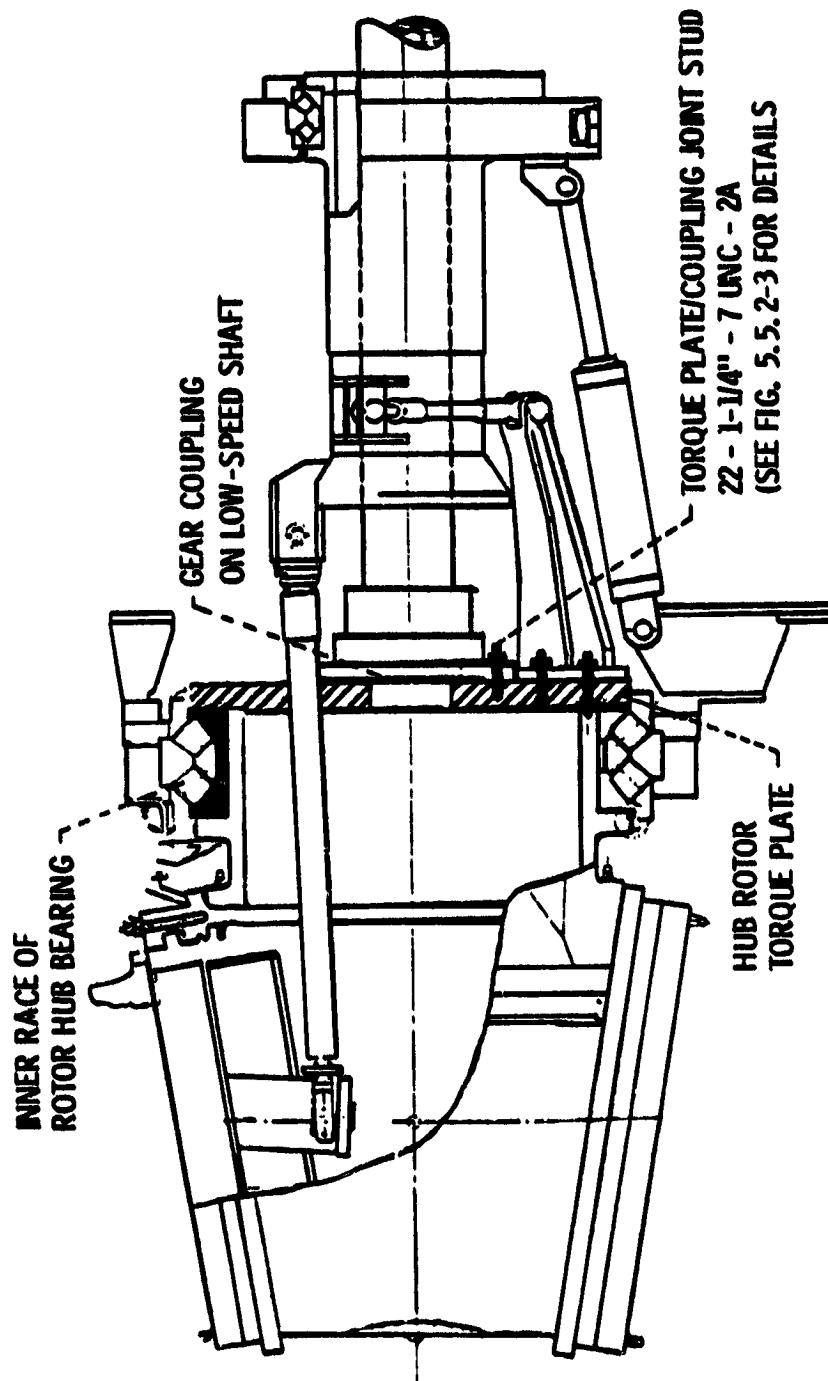


Figure 5.5.2-2 - Section view of hub/shaft interface showing studs location.



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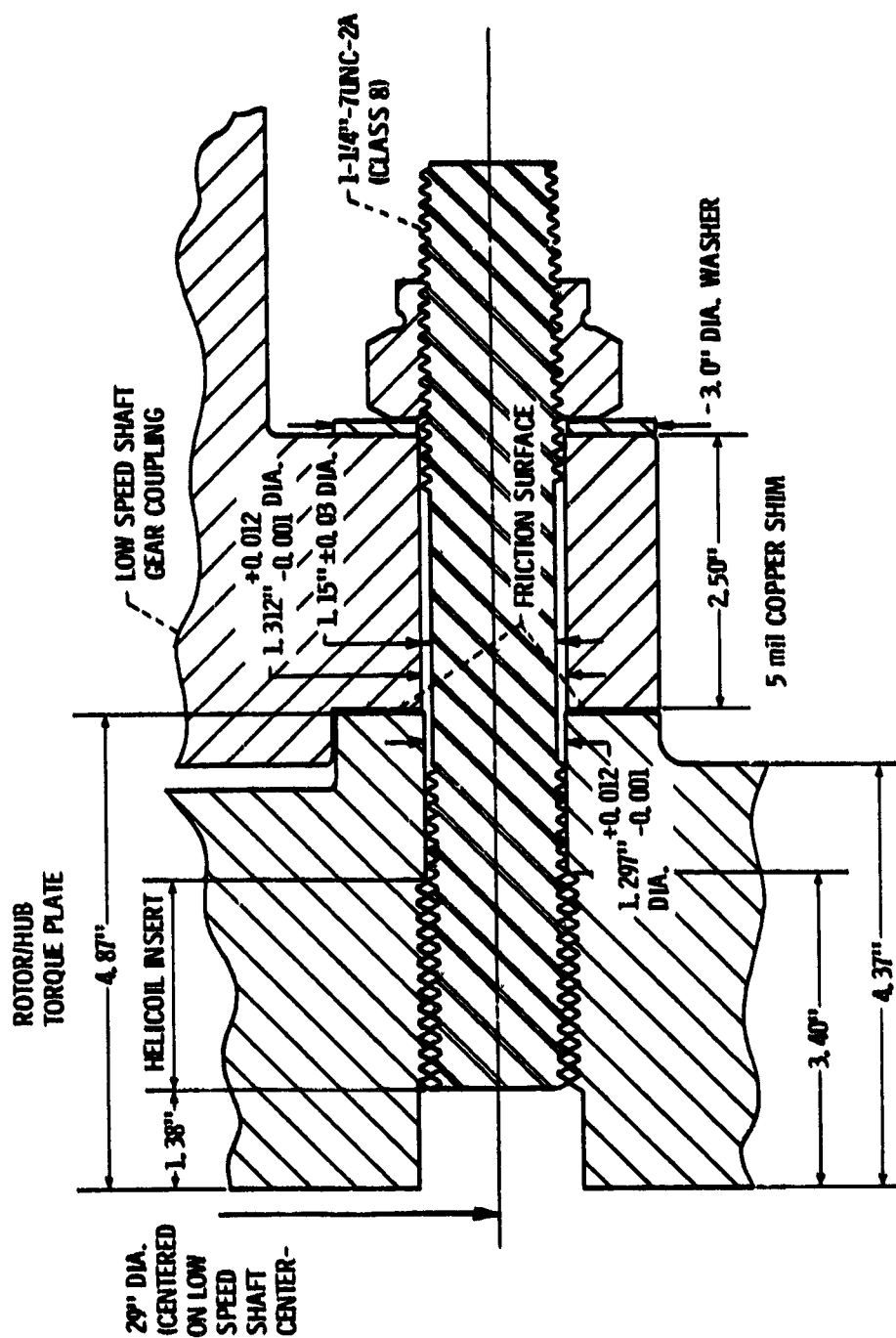


Figure 5.5.2-3. - Torque plate/coupling joint (stud detail).

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<b>ANLOR</b>		<b>TRANSMISSION</b>	
Number of blades . . . . .	3	Type . . . . .	Three-stage conventional
Diameter, ft . . . . .	200	Ratio . . . . .	31
Speed, rpm . . . . .	35	Rating, hp . . . . .	2209
Direction of rotation . . . . .	Counterclockwise (looking upwind)	<b>GENERATOR</b>	
Location relative to tower . . . . .	Downwind	Type . . . . .	Synchronous ac
Type of hub . . . . .	Rigid	Rating, kVA . . . . .	3225
Method of power regulation . . . . .	Variable pitch	Power factor . . . . .	0.8
Cone angle, deg. . . . .	9	Voltage, V . . . . .	4160 (three phase)
Tilt angle, deg. . . . .	0	Speed, rpm . . . . .	1800
<b>Blade</b>		Frequency, Hz . . . . .	50
Length, ft . . . . .	100	<b>Orientation drive</b>	
Material . . . . .	Steel spar/foam trailing edge	Type . . . . .	Ring-gear
Weight, lb/blade . . . . .	21,500	Yaw rate, deg/sec. . . . .	25
Airfoil . . . . .	NACA 44XX	Yaw drive . . . . .	Hydraulic
Twist, deg. . . . .	11	<b>Control system</b>	
Tip chord, ft. . . . .	3.8	Supervisory . . . . .	Computer
Root chord, ft. . . . .	12	Pitch actuator . . . . .	Hydraulic
Chord taper . . . . .	Linear	<b>Performance</b>	
<b>Tower</b>		Rated power, kW . . . . .	2 000
Type . . . . .	Pipe truss	Wind speed at 30 ft, mph . . . . .	11
Height, ft . . . . .	131	Cut-in . . . . .	25.5
Ground clearance, ft . . . . .	40	Rated . . . . .	35
Hub height, ft . . . . .	140	Cut-out . . . . .	125
Access . . . . .	Noise	Manuel. design . . . . .	125

TABLE 4.1-1 - DESIGN SPECIFICATIONS FOR MOD-1 WIND TURBINE GENERATOR

	Weight, lb
<b>Rotor assembly</b>	
Hub	15,000
Blades	41,000
Bearings and structure	29,000
Pitch-change mechanism	11,000
Pitch-control hydraulics	12,000
	108,000
<b>Nacelle assembly</b>	
Bedplate	68,000
Painting	5,000
Generator and exciter	14,000
Power generator equipment	1,000
Shafts, couplings, and clutch	18,000
Gearbox	38,000
Lubrication and hydraulic systems	4,000
Data acquisition system	1,000
Cables, lights, etc.	2,000
	171,000
<b>Yaw assembly</b>	
Bearing supports	47,000
Yaw brake	1,000
Yaw drive	8,000
	56,000
<b>Tower assembly</b>	
Structure	313,000
Elevator and miscellaneous	1,000
Cabling and conduit	6,000
	320,000
<b>Total (excluding ground equipment)</b>	655,000

TABLE 4.1-2 - WEIGHT BREAKDOWN OF MOD-1 WIND TURBINE GENERATOR

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Function	Additional Restrictive Conditions
Pitch to Any Angle ( $\pm 5^\circ$ )	Wind Speed* 15 mph
Yaw to Any Angle ( $\pm 5^\circ$ )	Wind Speed* 35 mph
Yaw Hydraulics Pump Motor On/Off	-
Hub to Any Angle ( $\pm 10^\circ$ )	Wind Speed* 25 mph
PCM Pump Motor On/Off	-
Release/Apply Yaw Brake	Wind Speed* 25 mph
Main Lube Pump On/Off	-
Hub to Any Speed ( $\pm 0.5$ rpm)	Break Away Wind Speed* 25 mph

\* Wind Speed measured at hub height

TABLE 5.2-1. Manual Functions

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Function	Description
Monitor Enable	Process Lockout Sensors, Initialize Commands
Initialization	Initialize Yaw, Pitch, and Lube Subsystems
Site Enable	Process Automatic Restart Sensors
Anti-Stall	Limit $\beta$ as a $f(V_W)$ to Prevent "Stall"
Overstress	Limit Structural Stress as a $f(V_W, \text{Yaw Error})$
Yaw Correct	Align Nacelle With Wind Vector
Pitch Ramp	Ramp $\beta$ $90^\circ$ to $72^\circ$ - Maximum Coefficient of Lift
Speed Ramp	Ramp Generator Speed 0 to 1200 rpm
Rate Sync	Set Freq. Generator = Freq. Utility
Voltage Sync	Set Voltage Generator = Voltage Utility
Angle Sync	Enable Switch Gear Synchronizer, Wait for Breaker Close
Power Ramp	Step Power in 25 kW Increments 2 Sec. Apart
Shutdown	Disengage Utility, Feather Blades, Brake, Park Rotor
Power Peaking	Iterate Power Set - Point to Max. Value for $11 \leq V_W \leq 24.6$

Table 5.2-2. Control System Functions

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Mode	Functional Description	Operating Conditions	
		Control Parameters	Wind Speed (mph)
Startup	Ramp Blade Pitch Angle to +72° With Shaft Brake On. Accelerate Rotor to Rated Speed by Pitching Blade Using Speed Schedule after releasing the brake.	<ul style="list-style-type: none"> <li>• Time</li> <li>• Shaft Speed</li> <li>• Blade Angle</li> </ul>	11 to 35
Rate Sync	Closed Loop Control of Pitch to Make f Utility = f Generator	<ul style="list-style-type: none"> <li>• Utility Frequency</li> <li>• Generator Speed</li> </ul>	11 to 35
Angle Sync	Closed Loop Control of Pitch to Make g Utility = g Generator	<ul style="list-style-type: none"> <li>• Utility Phase Angle</li> <li>• Generator Phase Angle</li> </ul>	11 to 35
Power Control	CPU Ramps Power Reference Command to Set Desired Power Output	<ul style="list-style-type: none"> <li>• Time</li> <li>• Generator Power</li> <li>• Blade Angle</li> </ul>	11 to 35
Manual	For Testing and Periodic "exercising," the Blade can be commanded Over the Full Range.	<ul style="list-style-type: none"> <li>• Manual</li> <li>• Blade Angle</li> <li>• Time</li> </ul>	0 to 25
Pitch Jam	"Pitch Jam" Status to NMU if Pitch Mechanism does not Respond to Position Control	<ul style="list-style-type: none"> <li>• Time</li> <li>• Voltage</li> </ul>	Any
Power Down	CPU Ramps Reference to Zero Power	<ul style="list-style-type: none"> <li>• Time</li> <li>• Generator Power</li> <li>• Blade Angle</li> </ul>	11 to 35
Slow Down	Reduce Rotor Shaft Speed to 1 rpm by Slewing Blade at 1 Deg/Sec	<ul style="list-style-type: none"> <li>• Blade Angle</li> <li>• Shaft Speed</li> </ul>	Any

Table 5.2-3. Pitch Control Modes of Operation

Wind Speed (mph)	Drive	Brake	Notes
0 to Cut-In	"Off"	"On"	No operation
CI to Cut-Out	Corrects for Yaw error of 5° for 5 minutes	"Off" when not rotating. "On" if RPM above 8 at lower pressure	0.25 deg/sec
Above CO	"OFF"	"On"	Shutdown
0 to Rated	Manual - to any angle	Manual	For Test

Table 5.2-4. Yaw Control

Type of Shutdown	Contract System Functions	Criteria for Shutdown
Normal	<ol style="list-style-type: none"> <li>1. Yaw Off if Failure</li> <li>2. Power Down (Pitch Change)</li> <li>3. Breaker Open</li> <li>4. Slow Down (Speed Kamp)</li> <li>5. Rotor Stop</li> <li>6. Apply Parking Brake</li> </ol>	Manual Command Dispatcher Command Wind Speed Drops Below 11 MPH User Subsystem Failure Wind Speed - Yaw Error Out of Band Temperatures Out of Band Average Wind Speed Above 35 MPH Emergency Pitch Hydraulic Pressure Low
Emergency	<ol style="list-style-type: none"> <li>1. Yaw Off if Failure</li> <li>2. Pitch Emergency Feather</li> <li>3. Breaker Open</li> <li>4. Rotor Stop</li> <li>5. Apply Parking Brake</li> </ol>	Frequency Out of Band Shaft Speed too High Main Breaker Open while in Gen Utility Voltage LDip Below Limit Wind Speed-Yaw Error Out of Band Any Vibration Above Limit Data Link Anomaly
Utility Outage	Emergency Feather, Yaw Motor Off, Brake On, Shaft Brake Off	Utility Voltage Drops Out
Pitch Jam	<ol style="list-style-type: none"> <li>1. Emergency Feather</li> <li>2. Yaw 90° to Wind &amp; Track</li> </ol>	Blade Will Not Respond

Table 5.2-5. Shutdown Logic

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TABLE 5.3.1-1 - TV CHANNELS AVAILABLE IN BOONE

Channel	Station Location	Network Affil.	Effec. rad. visual power (kW)	Antenna Location Latitude	Antenna Location Longitude	Distance from WT (in km)	Direction to Trans. (deg. from N)
2(a)	Sneedville, TN	ABC	100	36°22'52"	83°10'48"	134	278
2(b)	Greensboro, NC	CBS	100	35°52'13"	79°50'25"	170	103
3	Charlotte, NC	CBS	100	35°17'50"	81°06'53"	116	154
5	Bristol, VA	NBC	85.1	36°26'57"	82°06'31"	46	302
7	Spartanburg, SC	CBS	294.4	35°10'12"	82°17'26"	130	205
8	High Point, NC	None	316	35°48'47"	79°50'36"	171	105
9	Charlotte, NC	ABC	316	35°15'41"	80°43'38"	138	141
11	Johnson City, TN	CBS	245	36°25'55"	82°08'15"	47	299
12	Winston-Salem, NC	NBC	316	36°22'31"	80°22'27"	118	82



QUESTIONS AND ANSWERS

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J. L. Collins

From: P. A. Bergman

Q: What was the reasoning for suggesting that heli-coil type inserts not be used in connections?

A: *Heli-coil insert type joints are not recommended for friction type joints. The specific objections are listed below.*

- 1) There is concern that the heli-coil insert will give by the thread rolling over slightly. For most bolted type joints, a slight relaxation is permissible; but for a friction joint that depends on a fixed clamping force, any relaxation is not tolerable.*
- 2) The heli-coil has a self locking feature which makes it difficult to inspect. I prefer a positive mechanical locking type device that can easily be inspected on both ends of the fastener.*
- 3) On our particular installation, the clearance between the hole and stud shank allowed bending in the stud from torque loading on the joint. A through bolt type fastener would allow less clearance between the shank and the hole thus eliminating fastener bending and increasing the shear capability of the joint.*

From: C. Tan

Q: Have you experienced icing problems? Are they severe? If so, what can be done to cope with this problem in the future?

A: *Mod-1 has experienced icing on the tower and blades, but not severe enough to shut the machine down. Since the Mod-1 is a research machine and not operating on a continuous basis, there may have been occasional severe icing which would have prevented operation. Anti-icing systems can be installed on the blades of machines that operate in climates where icing is rather common. These systems would be similar to those on aircraft wings.*

From: B. Barron

Q: What was the source of torque overloads?

- A:
- 1) Torque overloads were caused by wind gusts which were not handled by the slip clutch. The slip clutch operation and set point were not consistent.*
  - 2) The control system checkout was somewhat rough on the drive train.*
  - 3) Motoring occurred due to late breaker opening.*

From: P. J. Pekarul

- Q:
- 1) What caused the preload failure?*
  - 2) Please discuss the compliance in the Mod-1 drive train.*

- A: 1) The preload failure was caused at the time of installation of the stud fasteners in the joint. The nuts were not properly torqued. The clearance between the stud shank and hole in the torque plate/coupling allowed bending in the studs. These studs then failed in low cycle bending fatigue. See Figures 5.52-1, 5.52-2 and 5.52-3 for details.
- 2) The compliance of the Mod-1 drive train is dominated by the low speed shaft and gearbox. The torsional natural frequency is .7 P at 35 RPM. For a complete description of the machine, a review of the Mod-1 design report is recommended, which is reference 4 of this paper.

From: Anonymous

Q: What computer codes were verified and how extensive was the verification?

A: We verified the GETTS code which is a General Electric dynamic and loads program. The code has been verified for three cases 1) Mod-1 rigid hub, 2) Mod-0 rigid hub, and 3) Mod-0 teetered hub.

From: R. Pratt

Q: Will Mod-1 be converted to an up-wind machine to eliminate noise problems?

A: There are no plans to convert the Mod-1 to an up-wind machine either for a test configuration or permanent conversion. Converting the Mod-1 to an up-wind machine has been studied and could be accomplished. However, there would be severe limits imposed on the machine in terms of power capability, cut-out wind speed, etc. This would be a significant change from the original machine design.

From: J. S. Wood, Jr.

Q: Concerning wind turbine noise decibel readings: 1) What scales were used? 2) Instant or sustained levels? 3) What frequencies were listened for?

A: Sound decibel readings were taken for 30 minutes about the 315 Hz active band with no filtering. The sound data has been reported in reference 10 of this paper and also was published in the Wind Turbine Dynamics Workshop held at Cleveland State University, Cleveland, Ohio, February 24-26, 1981. The proceedings are published and identified as NASA Conference Publication 2185 or DOE Publication CONF-810226 and entitled "Wind Turbine Dynamics."

From: G. G. Biro

Q: What are the response times at low and high wind speed cut-in and cut-out?

J. L. Collins (continued)

A: *The Mod-1 takes about 10 minutes to synchronize in either high or low winds. It takes between 1 and 2 minutes to shutdown under normal conditions and about 10 seconds for an emergency shutdown.*

From: J. Westergaard

Q: Your chart noted "Concepts to Reduce Cost." Were all of these concepts shown on the Mod-1A sketch or are there additional concepts and ideas you could mention?

A: *The Mod-1A includes a majority of the concepts that would result in a more cost competitive future wind turbine design. One item not mentioned in the Mod-1A description would be to replace the computer in the control system with a microprocessor. The initial capital and maintenance costs would be less for the microprocessor.*

From: G. G. Biro

Q: What were the operation and maintenance costs?

A: *Based on the Mod-1 experience, operation and maintenance costs cannot be firmly established. This is because it is impossible to separate costs for test support and machine configuration changes from normal operation and maintenance costs.*

From: A. Jagtiani

Q: Will this machine be modified, repaired and re-used or will it be removed or left in Boone as a monument?

A: *The federal funding level will really determine whether the Mod-1 will be repaired. Even though the program has been very successful, there is additional information on wind turbine technology that could be gained by the continued operation of the Mod-1 machine.*

## DESCRIPTION OF THE 3MW SWT-3 WIND TURBINE AT SAN GORGONIO PASS CALIFORNIA

S. C. Rybak

The Bendix Corporation Energy, Environment and Technology Office

### Abstract

The SWT-3 wind turbine, developed under an agreement between Bendix and Southern California Edison (SCE), is a microprocessor controlled three bladed variable speed upwind machine with a 3MW rating that is presently operational and undergoing system testing at SCE's Devers Substation ten miles north of Palm Springs California. The tower, a rigid triangular truss configuration, is rotated about its vertical axis to position the wind turbine into the prevailing wind. The blades rotate at variable speed in order to maintain an optimum 6:1 tip speed ratio between cut-in and rated wind velocity thereby maximizing power extraction from the wind. Rotor variable speed is implemented by the use of a hydrostatic transmission consisting of fourteen fixed displacement pumps operating in conjunction with eighteen variable displacement motors. Full blade pitch with on-off hydraulic actuation is used to maintain 3MW of output power between rated wind velocity of 40 mph and the cut-out wind velocity of 55 mph.

### 1.0 INTRODUCTION

In a privately funded venture, The Bendix Corporation in conjunction with Southern California Edison (SCE) Company developed and erected the SWT-3 wind turbine at SCE's Devers substation in the San Gorgonio Pass area ten miles north of Palm Springs, California. The SWT-3 has a 3MW rating and its design is based on the technology developed by Mr. Charles Schachle. The wind turbine is presently operational and is undergoing system testing to determine/verify performance characteristics. This paper describes the configuration of the SWT-3 and includes a description of major control subsystems operation as well as a brief report on the present machine status.

### 2.0 PHYSICAL CONFIGURATION OF THE SWT-3 WIND TURBINE

The SWT-3 wind turbine is a three bladed variable speed upwind rotor machine which employs a nacelle enclosed machinery bedplate rigidly fixed to a steel truss tower. The approximately 100 feet high tower employs a pyramid shape with a triangular base configuration approximately 75 foot on each side. The tower is rotated about its vertical axis to position the wind turbine into the

prevailing wind. Rotor variable rotational speed is obtained by means of a hydrostatic transmission consisting of 14 fixed displacement pumps, 18 variable displacement motors and the associated plumbing. The fixed displacement pumps are located in the nacelle and are driven by the rotor through a step-up gear box. The variable displacement motors are located at the base of the tower in a generator enclosure and are tied to the generator through another step-up gear box. High pressure hydraulic lines run from the fixed displacement pumps to the variable displacement motors linking the two and forming the power transmission path. Three charge pumps supply fluid from a reservoir to the low pressure side of the fixed displacement pumps thus completing the primary power loop. Pitch control is achieved by rotating the blades about their longitudinal axis using an on-off hydraulic actuation system. All control and housekeeping functions are microprocessor controlled, however for various critical functions whose failure could either impact system safety or result in severe wind turbine damage, hard wire loops are implemented in parallel with the microprocessor to insure that those critical operational areas are properly maintained in the event of a microprocessor failure.

A schematic diagram of the SWT-3 wind turbine is shown in Figure 1.0. The major components comprising the drive/power train is schematically shown in Figure 2.0. A top level block diagram of the microprocessor and its interaction with the wind turbine system is shown in Figure 3.0. A summary of the SWT-3 specifications and performance characteristics is given in Table 1.0. Figure 4.0 shows the estimated yearly energy gathering capability of the SWT-3 wind turbine as a function of average wind velocity at hub height. Figure 5.0 shows the estimated power output as a function of average wind velocity at hub height. A more detailed description of the SWT-3 design and control system operation is given in the paragraphs that follow.

### 3.0 OVERALL WIND TURBINE SYSTEM DESCRIPTION

The SWT-3 wind turbine was designed to produce 3MW of electrical power output in a prevailing wind of 40 mph at a rotor rotational speed of 41 rpm. The wind turbine design allows for operation in wind speeds between 8 and 55 mph once the wind turbine has been turned on. However for the wind turbine to be activated the prevailing wind must be between 12 and 55 mph. For winds in excess of 55 mph the wind turbine will not turn on, or if operating will automatically shut itself off.

Three major subsystems control the SWT-3 wind turbine. They are the rotor speed control subsystem, the blade pitch control subsystem, and the tower yaw control subsystem. A description of each of these control subsystems is given in what follows.

#### 3.1 Rotor Speed Control Subsystem

In order to extract the maximum amount of energy from the wind for wind speeds between 8 and 40 mph a 6 to 1 speed ratio must be maintained between the blade (rotor) tip speed and the wind velocity i.e., the blade tips must have a linear velocity which is six times that of the wind velocity perpendicular to the disc swept by the rotor. In order to maintain this speed ratio for wind speeds varying between 8 and 40 mph the rotor rpm needs to vary accordingly. For the geometry

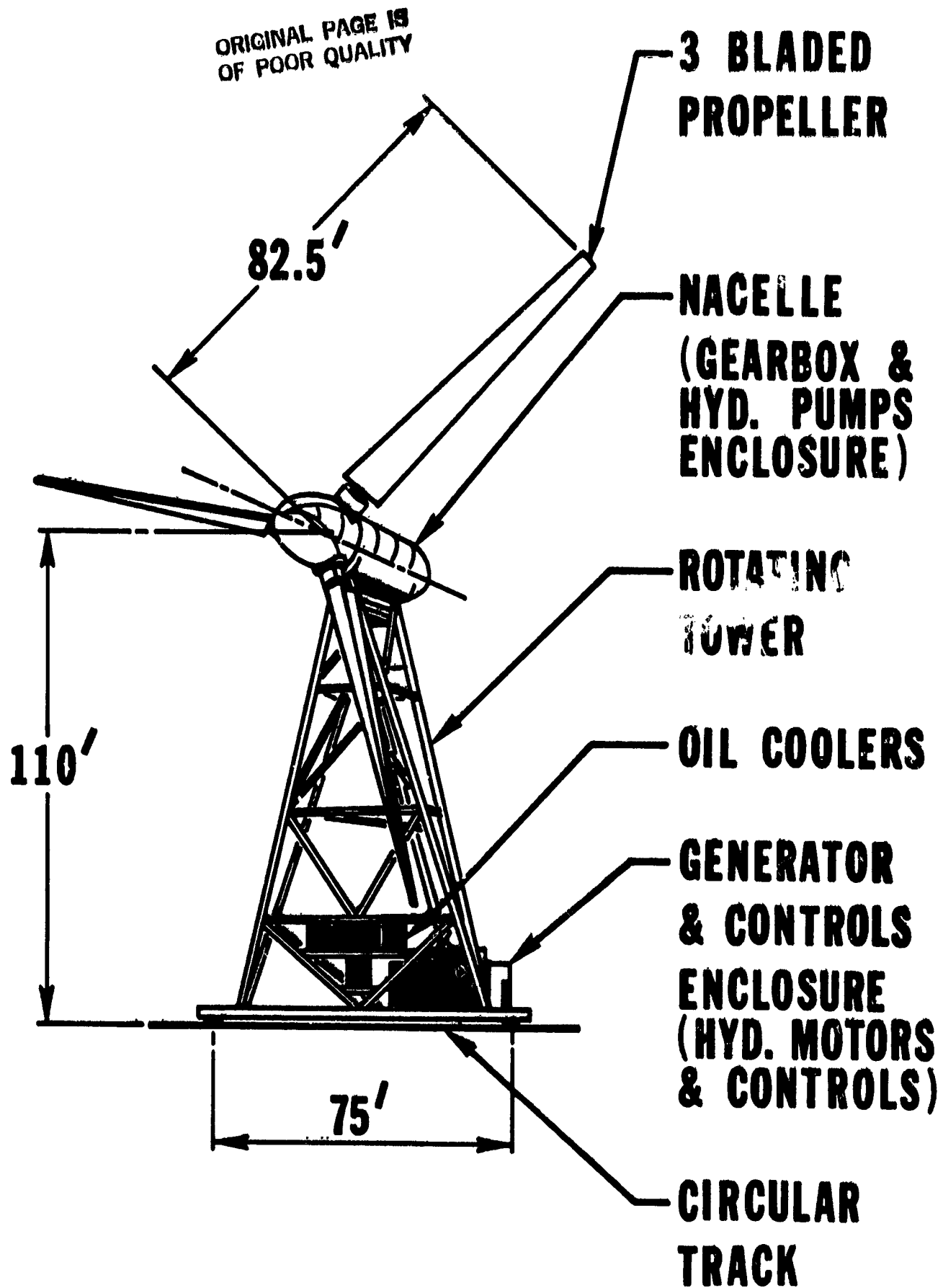


FIGURE 1.0 SCHEMATIC DIAGRAM OF SWT-3 WIND TURBINE

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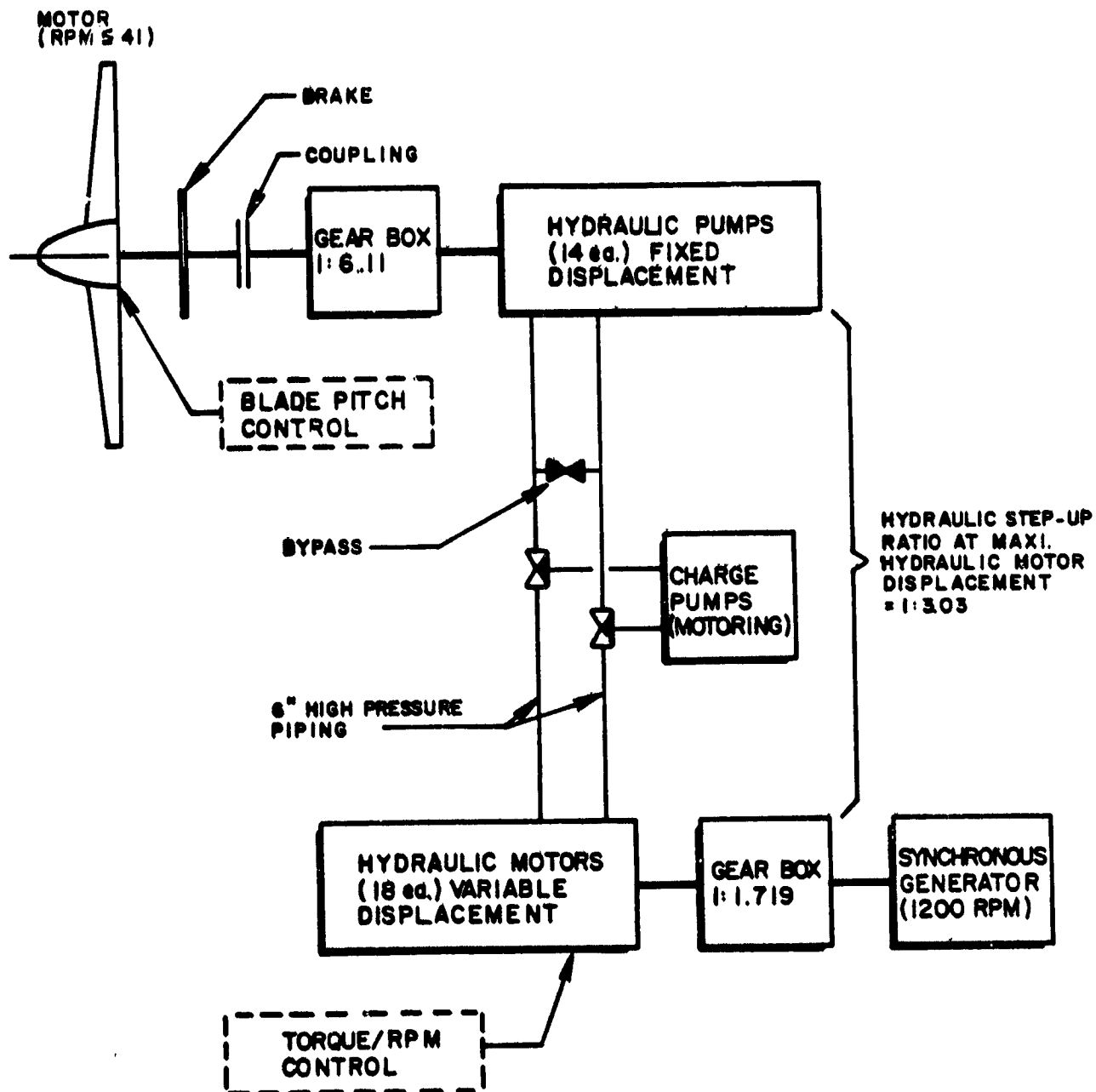


FIGURE 2.0 SCHEMATIC DIAGRAM OF SWT-3 DRIVE/POWER TRAIN

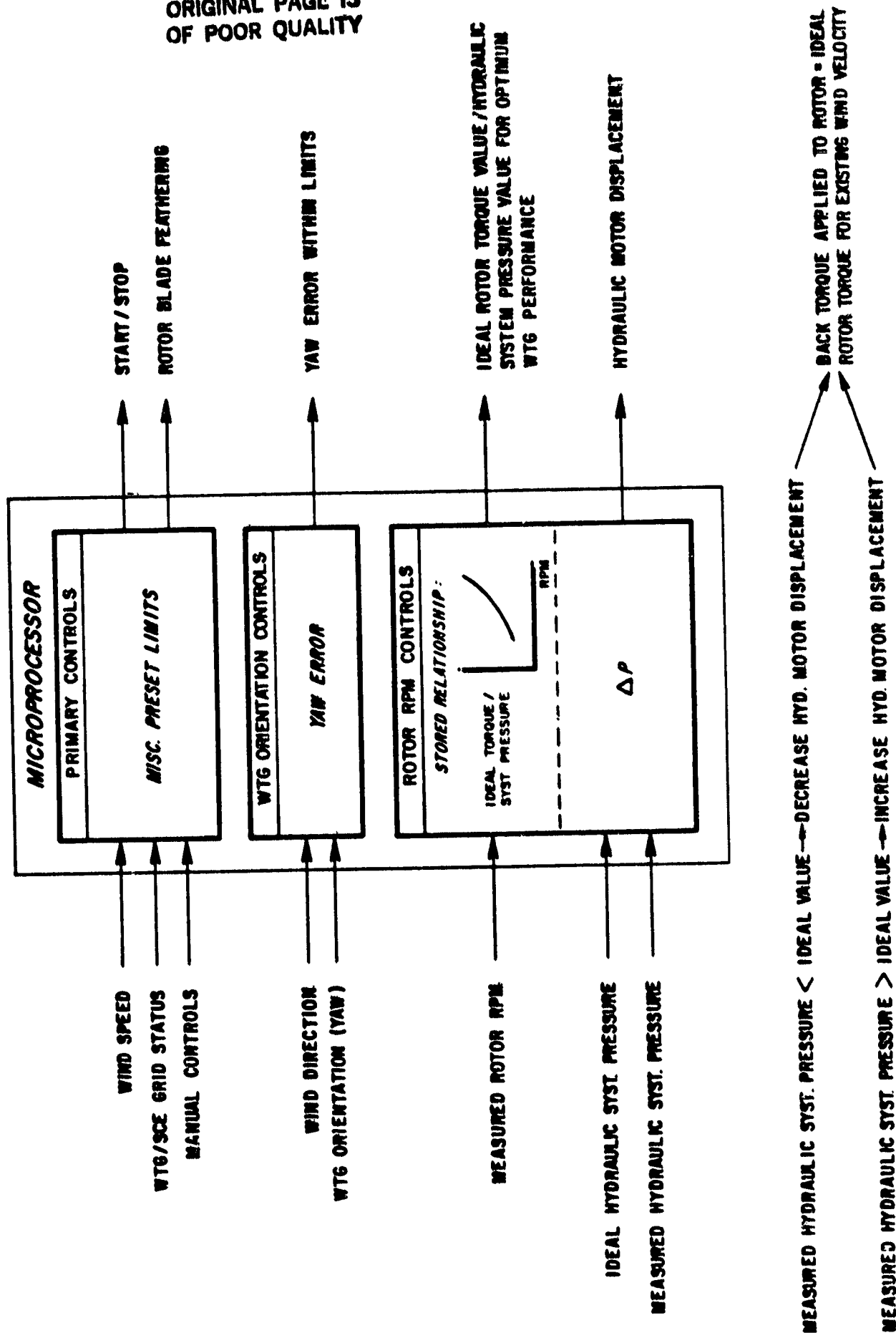


FIGURE 3.0 MICROPROCESSOR BLOCK DIAGRAM



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TABLE 1.0 BENDIX SWT-3 WIND TURBINE GENERATOR CHARACTERISTICS

RATED POWER	3,000 KW
ROTOR DIAMETER	169 FT
ROTOR TYPE	3-BLADE HORIZONTAL AXIS
ROTOR AIRFOIL	SCHACHLE
ROTOR ORIENTATION	UPWIND
ROTOR TIP SPEED	VARIABLE - 6 TIMES THE WIND VELOCITY
RATED WIND VELOCITY	40 MPH
ROTOR ROTATIONAL SPEED AT RATED POWER	41 RPM
CUT-IN WIND VELOCITY	12 MPH
CUT-OUT WIND VELOCITY (HIGH END)	55 MPH
CUT-OUT WIND VELOCITY (LOW END)	8 MPH
GENERATOR TYPE	SYNCHRONOUS
GENERATOR ROTATIONAL SPEED	1,200 RPM
GENERATOR VOLTAGE	4,160 VOLTS
POWER FACTOR	1.0 AT FULL LOAD
HARMONIC CONTENT	2%
DEVIATION FACTOR	3%
GENERATOR EFFICIENCY	96.5% AT FULL LOAD
GENERATOR ROTATIONAL SPEED	1,200 RPM
POWER TRANSMISSION SYSTEM	HYDROSTATIC (14 FIXED DISPLACEMENT PUMPS WITH 18 VARIABLE DISPLACEMENT MOTORS)
PUMP DISPLACEMENT	150.6 $\text{IN}^3$ /REV PER PUMP
MOTOR DISPLACEMENT	38.63 $\text{IN}^3$ /REV PER MOTOR MAXIMUM DISP. 11.4 $\text{IN}^3$ /REV PER MOTOR MINIMUM DISP.
UPPER GEAR BOX	HELICAL SPUR GEAR 1:6.11 STEP-UP
LOWER GEAR BOX	HELICAL SPUR GEAR 1:1.719 STEP-UP
PITCH CONTROL	HYDRAULIC ON-OFF ACTUATION
TOWER	TRIPOD CONFIGURATION, RIGID TRUSS CONSTRUCTION, ROTATING FOR YAW CONTROL
TOWER ROTATION SYSTEM	HYDRAULIC ON-OFF ACTUATION
HUB HEIGHT	110 FT
FOUNDATION	CIRCULAR - 78.5 FT DIAMETER
SYSTEM POWER COEFFICIENT	0.38 - FROM CUT-IN TO RATED POWER
AVAILABILITY FACTOR	0.95
TOWER YAW RATE	36 DEG/MIN
BLADE PITCHING RATE	1 $^\circ$ DEG/SEC NORMAL OPERATION 2 DEG/SEC EMERGENCY OPERATION

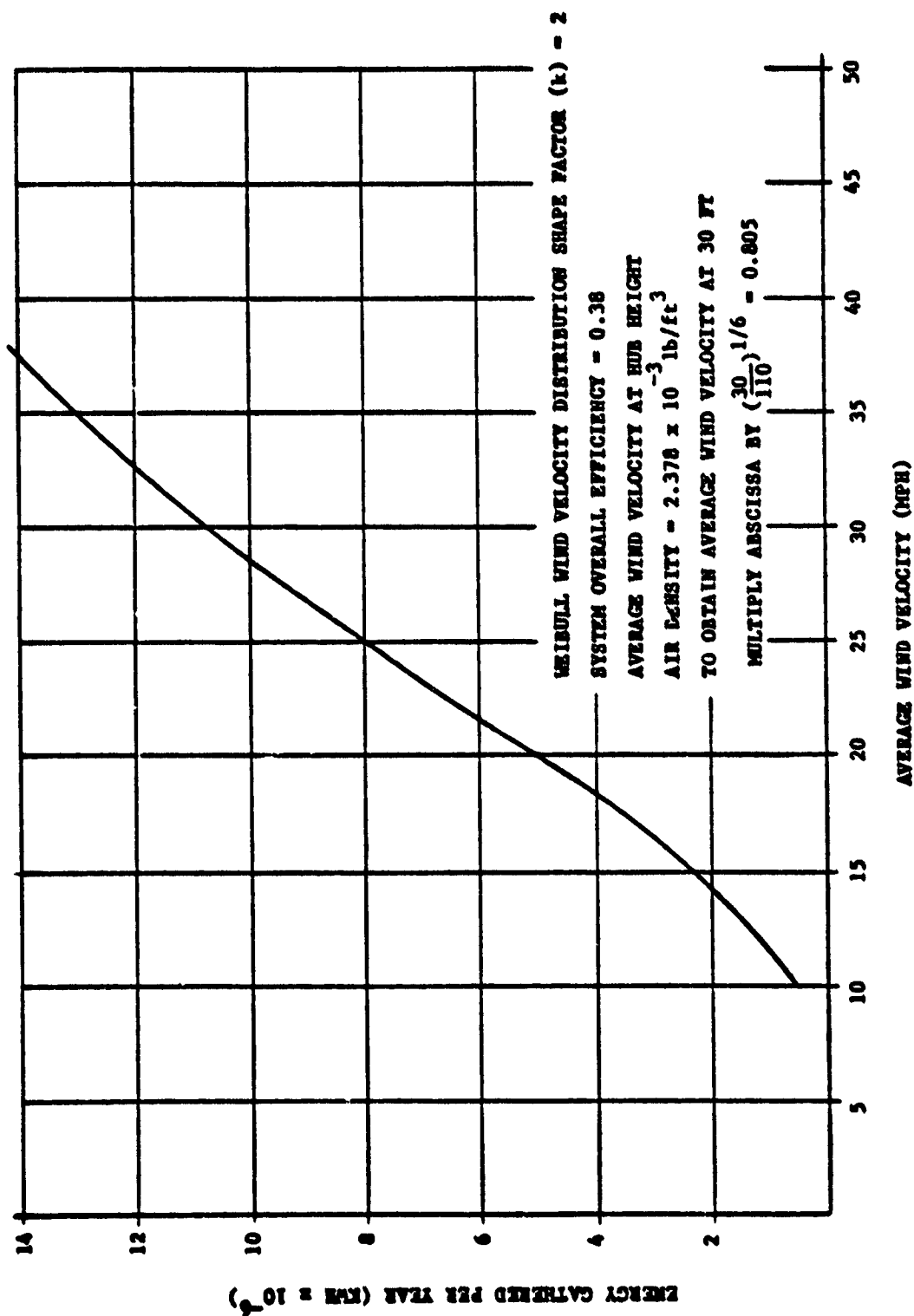


FIGURE 4.0 ENERGY GATHERED PER YEAR AS A FUNCTION OF AVERAGE WIND VELOCITY AT HUB HEIGHT (ESTIMATED)

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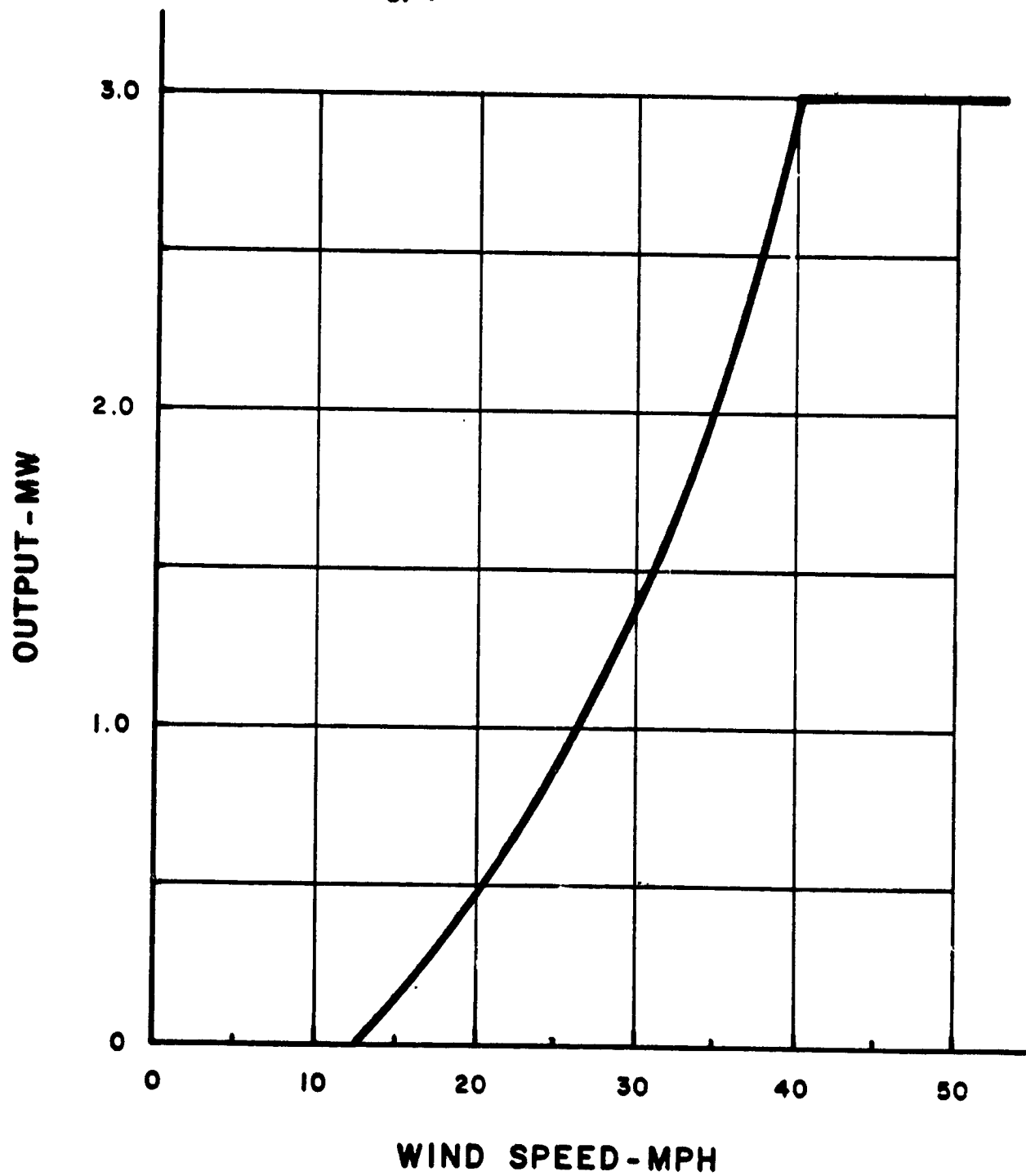


FIGURE 5.0 ESTIMATED OUTPUT POWER AS A FUNCTION OF AVERAGE  
WIND VELOCITY AT HUB HEIGHT

A block diagram of the rotor power/speed control loop intended to command the variable displacement motor is shown in Figure 6.0. The rotor rpm, as indicated by the tachometer mounted on the rotor shaft, is used to determine, from the microprocessor stored look-up table, what the system pressure should be for the particular rotor rpm. That system pressure in turn becomes the command pressure. The actual system pressure is measured by a pressure transducer which is passed through a low pass filter to avoid reacting to "high" frequency pressure spikes and to insure required loop stability and response characteristics. The system pressure is differenced with the command pressure and a pressure error determined. This error data is then passed through a variable speed deadband whose output commands the on-off solenoid valve thereby varying the motor displacements. The variable deadband methodology is employed to avoid/diminish speed control loop limit cycling which would in turn stress system components.

### 3.2 Rotor Pitch Control Subsystem

When the wind speed exceeds 40 mph but is below 55 mph the wind turbine will generate rated power (i.e. 3 MW) while the rotor speed is maintained at approximately 40 rpm. This is accomplished by pitching the rotor blades on the basis of system pressure limits (4,200 psi), rotor rpm limits (40 rpm), and generator speed limits (1,200 rpm). Pitching the rotor has the effect of maintaining the applied wind torque constant in wind regimes between 40 and 55 mph thereby maintaining rated power output. Actually, due to the on-off implementation of the pitch control, the blade pitch angle, and hence the power output, will limit cycle. The amplitude of the limit cycles are reduced to acceptable levels by the inclusion of appropriate loop compensation. A block diagram of the pitch control loop is shown in Figure 7.0.

When the pitch control loop is activated the system pressure will vary due to the blade pitching action. The rotor power/speed control loop uses this parameter in order to adjust the variable motor displacements to maintain optimum system pressure and rotor rpm. However, the curve relating system pressure to rotor rpm assumes that the rotor blades are at their optimum pitch. Therefore if the speed control loop is allowed to operate when the rotor blades are pitching, erroneous information will be fed into the power/speed control loop. Those signals will in turn erroneously and needlessly change motor displacement. In order to preclude such needless motor displacement changes the power/speed control loop is disabled when the blades are commanded to pitch.

### 3.3 Yaw Control Subsystem

The yaw control loop rotates the wind turbine into the wind so that the wind direction is within an acceptable angular error with respect to the perpendicular to the plane defined by the rotor blades. The control loop is implemented by having a tower mounted wind vane which measures the wind direction with respect to the tower. The wind vane signal is passed through a low pass filter in order to avoid responding to "short" term wind direction variations which otherwise would unduly stress the yaw control system actuation components.

Since the tower can only rotate  $330^{\circ}$  the command to the yaw actuator must take into consideration the angular position of the tower to avoid rotating it through its stops. This is accomplished by having an angular transducer which measures the tower angular position. The tower angular transducer measurement is added

of the SWT-3 wind turbine (i.e. blade tip to center of rotation of approximately 84.5 ft.) the rotor rpm should approximately equal the velocity of the wind given in mph to maintain the 6:1 speed ratio. However, the generator, to which the rotor is coupled, is a synchronous machine running at a constant 1,200 rpm. Therefore, if the rotor speed is to vary, the rotor must be coupled to the synchronous generator through a variable speed (i.e. gear ratio) transmission.

The variable speed transmission employed utilizes hydrostatic principles which are implemented by fourteen fixed displacement pumps operating in conjunction with eighteen variable displacement motors. As the motor displacements are varied the effective gear ratio between the rotor and the synchronous generator varies accordingly, allowing the rotor to rotate at varying rates while maintaining a constant rotation rate at the synchronous generator.

To maintain the rotor at a particular desired rpm the summation of the torques applied to the rotor must equal zero. The torques applied to the rotor consist of those applied by the wind ( $T_w$ ), the back torque applied by the synchronous generator through the hydraulics reflected to the rotor shaft ( $T_g$ ), and the torque applied to the rotor due to losses in the system ( $T_l$ ). Therefore the following relationship must apply for the rotor to remain in equilibrium and maintain constant speed.

$$T_w - T_g - T_l = 0 \quad (1)$$

Assuming that the system losses are small or  $T_l \ll 1$  then the following applies

$$T_w \approx T_g \quad (2)$$

Consequently it is clear that for the rotor to maintain constant rpm, the torque applied by the wind on the rotor must be approximately counterbalanced by the torque applied to the rotor by the generator through the system hydraulics. This torque is directly proportional to the pressure in the main hydraulic lines under steady state conditions. When the variable motor displacements are set to a value corresponding to a gear ratio  $N_g$ , which in turn corresponds to a particular rotor speed for a synchronous generator speed of 1,200 rpm, the pressure in the hydraulic lines will increase to a point where the back torque applied to the rotor approximately equals the torque applied by the wind to the rotor thereby keeping it in equilibrium and maintaining its speed constant at a value corresponding to the hydraulic motor displacement setting. If the relationship between the applied wind torque on the rotor as a function of rotor rpm is known, assuming the optimum speed ratio of 6:1 is maintained, measurement of the generator applied torque compared to the value of torque one should have for a particular rotor rpm will establish whether this value is proper for the measured rotor rpm. Depending whether the generator applied torque is greater or less than the optimum value for the measured rotor rpm the hydraulic motor displacement can be increased or decreased respectively until the optimum pressure and rotor rpm occur simultaneously. Since the applied generator torque acting through the system hydraulics is in the steady state directly proportional to system hydraulic pressure, system pressure could be measured in lieu of measuring the applied torque directly. Measurement of system pressure is considerably easier than measurement of the torque applied by the generator consequently system pressure measurement is used to implement the rotor speed control loop.

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$P_{co}$  = COMMAND PRESSURE

$P_s$  = SYSTEM PRESSURE

$\theta_{pc}$  = PITCH ANGLE COMMAND

$\theta_{plm}$  = MEASURED PITCH ANGLE

$T_a$  = TORQUE APPLIED TO THE ROTOR BY WIND

$T_c$  = TORQUE APPLIED TO THE ROTOR BY HYDRAULICS

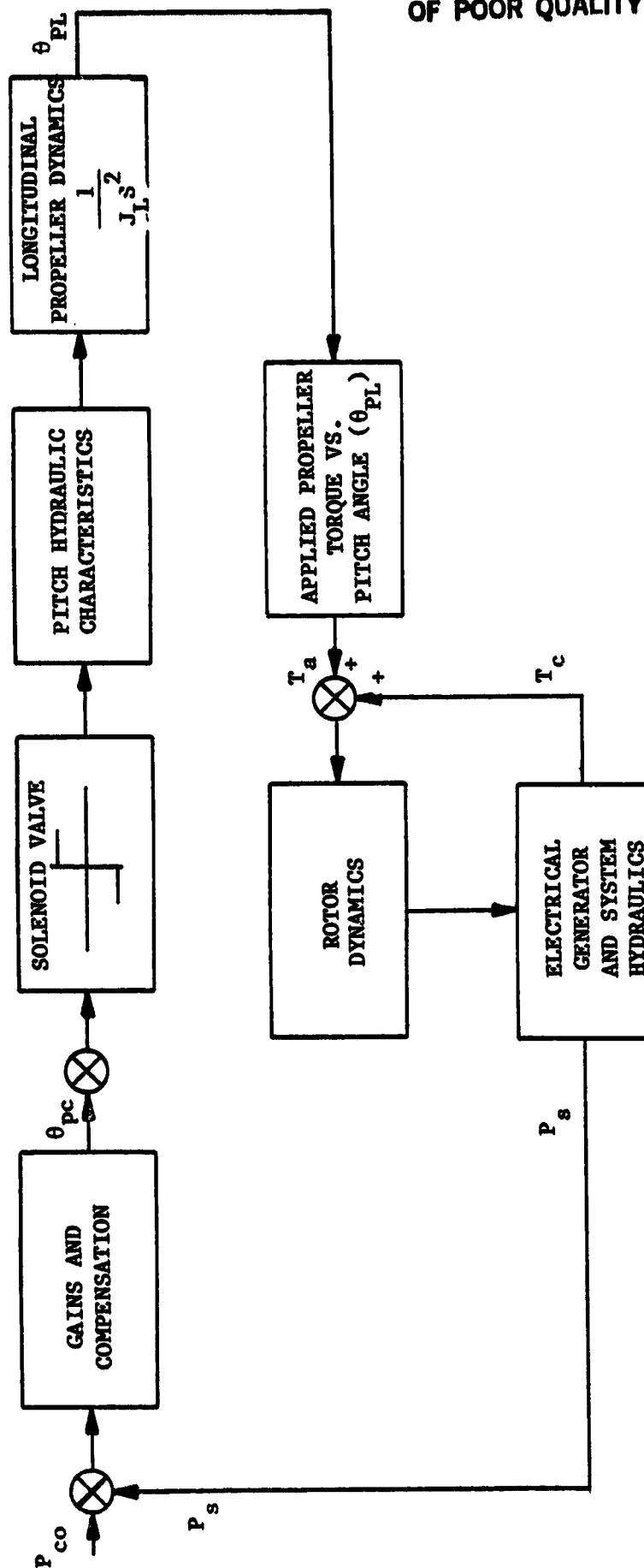


FIGURE 7.0 BLADE PITCH CONTROL LOOP

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to the wind vane measurement (which measures the wind direction relative to the tower) to obtain the tower command angle. The tower command angle is examined to determine if it is larger than  $360^\circ$ . (This condition can happen since both the tower angular transducer and the anemometer read positive angles between  $0^\circ$  and  $360^\circ$  when they rotate counterclockwise). If the tower command angle exceeds  $360^\circ$  then  $360^\circ$  is subtracted from the command and the new tower command angle is obtained. If the tower command angle does not exceed  $360^\circ$  then it becomes the new tower command angle. The tower command angle thus generated is then screened to determine if it is in the allowable region for tower angular position. If the new tower angular command is in the region between  $330^\circ$  and  $360^\circ$  it is then determined if the new tower command angle is less or greater than  $345^\circ$  (i.e. midpoint of the region the tower cannot rotate through). If the new tower command angle is between  $330^\circ$  and  $345^\circ$  the tower will be commanded to rotate to  $330^\circ$ . If the new tower command angle is between  $345^\circ$  and  $360^\circ$  the tower will be commanded to zero degrees. However, should it be necessary to command the wind turbine to initially rotate away from the prevailing wind direction in order to avoid the tower stops, it may be necessary to take the wind turbine off-line to avoid stressing the blades and causing the generator to excessively motor. The necessity of taking the wind turbine off-line under those conditions is still under evaluation, however the control algorithms required can easily be accommodated by the microprocessor.

A block diagram of yaw control loop is shown in Figure 8.0. As seen from the figure a variable deadband implementation is used to avoid chasing the wind thereby eliminating excessive yaw actuations which would otherwise result in the presence of relatively small wind variations.

#### 4.0 SWT-3 STATUS

The SWT-3 wind turbine was officially commissioned on December 16, 1980. Since that time the wind turbine has been under going system testing in order to determine and verify system stability and performance characteristics. Early in the testing program it became apparent that modifications would be required in the grid synchronization procedure in order to reliably put the wind turbine on-line. The modifications included the addition of a synchroscope and alterations to the control logic for the variable displacement motors. Once these modifications were implemented the wind turbine synchronization to the grid is reliable and operates smoothly.

The wind turbine operational envelope has been steadily expanded as system test and checkout proceeds. At present the wind turbine has generated approximately 1.1 MW of power at a rotor rotational speed of 21 rpm.

#### ACKNOWLEDGEMENT

The author expresses his gratitude to the Southern California Edison Company for their overall interest and assistance in preparation of the above paper. In particular the author would like to acknowledge that the schematic diagrams of the wind turbine (Figure 1.0) and the drive/power train (Figure 2.0), the microprocessor block diagram (Figure 3.0) and the estimated wind turbine output power as a function of wind speed (Figure 5.0) used in the paper to enhance the description of the SWT-3, was furnished by Mr. Michel Wehrey of the Southern California Edison Company.



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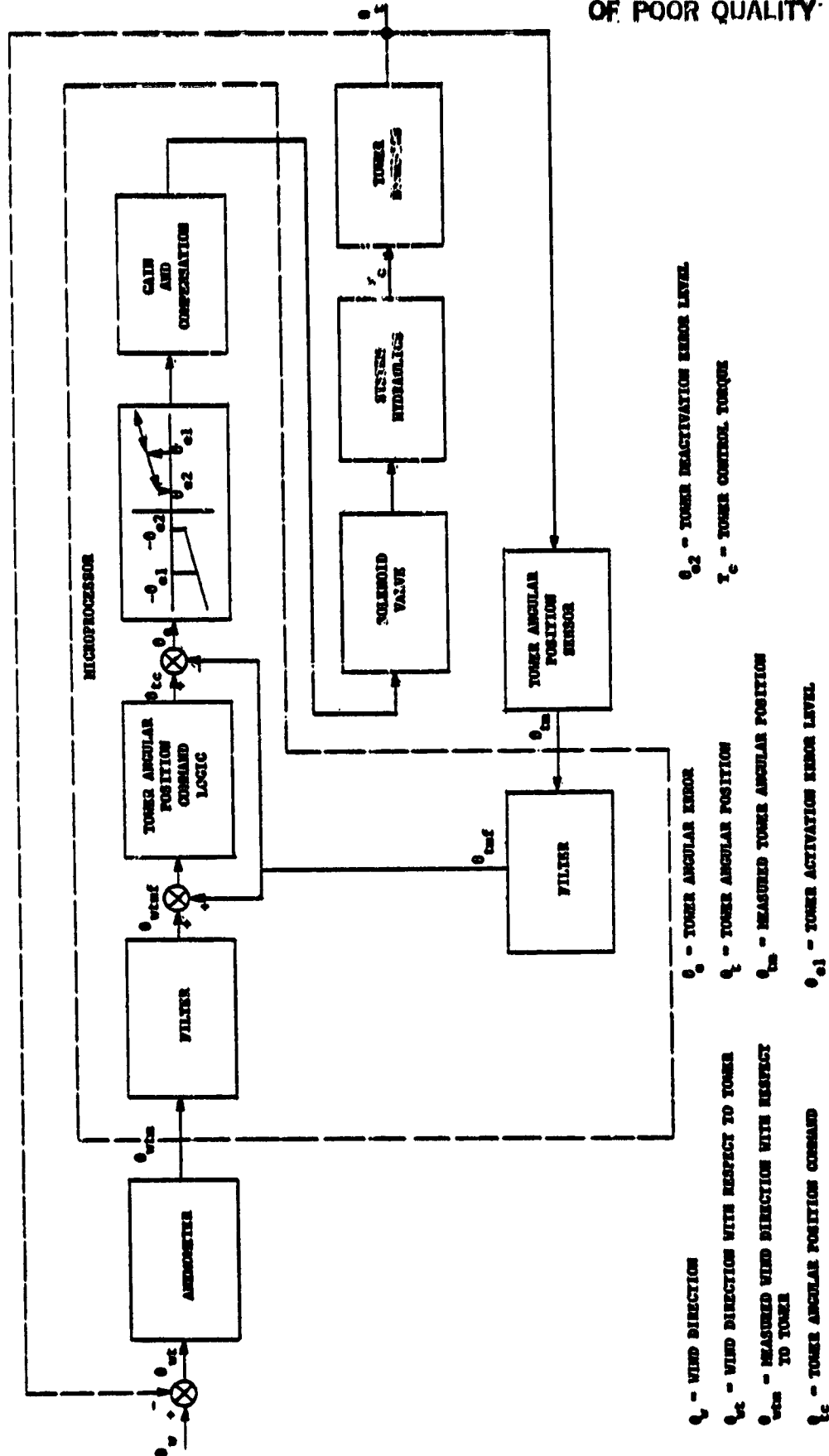


FIGURE 8.0 YAW CONTROL LOOP

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QUESTIONS AND ANSWERS

S. C. Rybak

From: A. Gustafsson

Q: What is the estimated and/or measured losses in the hydraulic drive system?

A: *The loss in the hydraulic drive system is approximately 25 percent.*

From: A. S. Jagtiani

Q: What is the 1) initial cost of the machine, 2) expected annual cost of the maintenance and operation, 3) overhead cost, and 4) cost per kilowatt-hour of generation?

A: *The SWT-3 is an experimental machine and as such its costs are not indicative of the costs of a commercially viable wind turbine.*

From: A. Swift

Q: What are the losses in the hydraulic pump and motor system?

A: *The losses in the hydraulic pump and motor system (i.e. excluding the generator) are approximately 78 percent.*

From: G. G. Biro

Q: What are the operation and maintenance costs and the station power assistance costs?

A: *Due to the experimental nature of the machine, the operation and maintenance costs do not have any real bearing on the costs for a commercially viable wind turbine.*

From: J. M. Medaglia

Q: Please discuss the weights, the cost of energy, and the maintenance of this system.

A: *The nacelle and components, including the blades, weigh approximately 280,000 lbs. The tower, including the generation equipment, weighs approximately 520,000 lbs, yielding approximately 800,000 lbs above the foundation. Due to the experimental nature of the machine, operation and maintenance costs have no bearing on the costs for a commercially viable wind turbine.*

From: M. Waters

Q: What is the hydraulic fluids makeup requirements in gallons per kilowatt-hour of energy delivered?

S. C. Rybak (continued)

A: *There are no hydraulic makeup requirements if the system does not leak.*

From: G. G. Biro

Q: What are the response times at cut-in and cut-out for low and high wind conditions?

A: *There is not enough test data at the present time to give a definitive answer.*

From: Anonymous

Q: What is the efficiency loss between rotor and generator? What is the expected life of the hydraulics?

A: *The loss between the rotor and generator is approximately 25 percent. At the present time it is not feasible to give a reasonable estimate of the life of the hydraulic system.*

From: G. C. Valentine

Q: Has blowing sand provided any maintenance/operational problems to date? Has this been specifically monitored?

A: *As far as we know, blowing sand has not been a significant contributor to operational and maintenance requirements to date.*

From: D. Lingelbach

Q: How much loss do you have in the gear-box hydraulic pump to hydraulic motor-gearbox drive train?

A: *The power transmission efficiency between main shaft power and generated power output is 75 percent.*

From: V. Weyers

Q: How many hours of operation have you achieved and what performance have you experienced?

A: *We have between 50 and 60 hours of on-line operation and approximately 1.1 Mw peak power has been generated. We have experienced various types of hydraulic problems that have caused delays and reduced the on-line operating time. These problems are presently being addressed.*

From: R. Herald

Q: How are the "ideal" rotor speed-hydraulic pressure relationships (i.e. the lookup table) determined? What happened to the 3 Mw that the unit is supposed to be able to generate?

S. C. Rybak (continued)

A: *The rotor speed vs. hydraulic pressure will be determined by system testing. At the present time we are slowly expanding the wind turbine performance envelope. The degree to which the 3 Mw rating can be approached will be due primarily to the blade loads encountered and the capability of the blades to withstand them.*

From: S. Rao

Q: 1) What is the efficiency of the pump system and the system as a whole?  
2) Do you have an accumulator between the pumps and drive motors?  
3) How do you start the wind turbine blades?

A: 1) *The efficiency of the power transmission system (i.e. from shaft power to electrical power output) is approximately 75 percent.*  
2) *There is no accumulator between the pumps and motors.*  
3) *The wind turbine is started via full span blade pitch control.*

From: R. Edkin

Q: How do you run variable speed using a synchronous generator?

A: *Variable speed is obtained by changing the motor displacement which requires a corresponding change in rotor rotational speed since it is directly geared to the fixed displacement pumps.*

From: A. Saunders

Q: Do you take the electric power off the tower via slip rings or cables?

A: *Electric power is extracted via slip rings.*

From: R. Edkin

Q: What is your experience with hydraulic problems such as leaks, and fluid contamination?

A: *Experience with the hydraulics indicates that the system is susceptible to leaks and fluid contamination. It does not appear that the hydraulic system will have the type of reliability that would be required of a commercial WECS.*

From: B. Barron

Q: What is the band width of the blade pitch control system?

A: *The bandwidth of the pitch control loop is between 1/2 and 1 Hz.*

OPERATIONAL EXPERIENCE ON THE MP-200 SERIES  
COMMERCIAL WIND TURBINE GENERATORS

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WTG Energy Systems, Inc.  
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Buffalo, New York 14203

ABSTRACT

Since incorporation in 1975, WTG Energy Systems, Inc. has dedicated itself to designing and manufacturing intermediate scale wind turbine generators. To date, we have installed three such generators, with a fourth scheduled to go on line by January 1982. Having accumulated thousands of operating hours in diverse utility environments, the MP-200 System wind turbines have demonstrated their potential as a viable commercial generating source. This presentation will describe some of the experience gained in the operation of these machines.

INTRODUCTION

WTG Energy Systems, Inc. was incorporated under the Laws of the State of New York in April, 1975 and is engaged in the design, fabrication, assembly and marketing of utility grade wind turbine electrical generating systems.

To date, the Company has fully designed, assembled and field tested the MP1-200, a 200 kilowatt wind turbine generator prototype. This machine is installed as part of the utility network of the Town of Gosnold on Cuttyhunk Island, Massachusetts. The MP1-200 was installed in July, 1977. The Company has entered into an agreement with the Gosnold Power and Light Commission which allows the Company to use the Town's electric power network as a test bed for performance evaluation, demonstration and advertising for its prototype unit.

WTG Energy Systems, Inc. sold their first production unit to the Nova Scotia Power Corporation. The MP2-200 System was installed at the Nova Scotia Power Corporation's Wreck Cove site in November, 1980. Nova Scotia Power Corporation will use this unit to pump water from a lake at a lower elevation to the reservoir at the Wreck Cove Hydro Plant, thereby increasing the capacity of the hydro facility.

Also in competitive bidding, WTG Energy Systems, Inc. was awarded the contract to furnish Pacific Power & Light Co. with the MP3-200 System. This unit was delivered to Pacific Power & Light's Whiskey Run site on the Pacific coast in December, 1980. The MP3-200 has been in operation since the Spring of 1981 and is being used by Pacific Power & Light as a research unit to determine the feasibility of wind generated electricity for the utility.

WTG Energy Systems, Inc. has recently completed the detailed design of a 600 kW wind generator. Production of this unit is anticipated to begin in the Fall of 1981.

The Company's progress, to date, has been governed by a design philosophy that incorporates the following guidelines:

The design and marketing of the Company's wind generators must be economically viable when compared to conventional generating sources.

The Company's products must incorporate off-the-shelf components and these products must be fabricated using conventional manufacturing techniques.

The product design must lend itself to field erection to both easy access and remote sites and this design must be flexible to meet various interface requirements.

Recognizing that field maintenance and repairs are a prime life cycle cost consideration, a product design must evolve that minimizes O & M requirements, permits service by technicians familiar with conventional generating equipment, and anticipates a product life of 30 years.

The wind generator and its electrical system must impose no hazard to the public, its operators or the interconnected system.

These considerations have been the driving parameters in the design and development of the MP-200 System design.

#### MP-200 SYSTEM DESIGN

The MP-200 System mechanical, hydraulic and electrical control systems are briefly described as follows.

## Mechanical System

The MP-200 System is illustrated in Figure 1, and consists of a three-bladed steel rotor, upwind, which is supported by a shaft integral to the transmission. The constant 30 RPM rotor speed is increased through a 40:1 gear box and delivers 1200 RPM to a 6-pole, 350 KVA synchronous alternator. Hydraulic power is supplied from a high pressure system mounted in the machine cabin, and is delivered to the tip flaps through a rotating union in the low speed shaft. Hydraulic power also operates the disc brake(s) on the high speed shaft and the yaw motors. Alignment with the wind is maintained by dual harmonic transmissions driving a bull gear. Yaw brakes lock the drive train to the tower. Details of the mechanical system are summarized in the MP-200 System Wind Turbine Specifications.

The tip flaps control the aerodynamic torque of the rotor by varying the aerodynamic lift and increasing the drag on the airfoil. In the deployed position, the flaps are 60 degrees out of the airfoil plane. The tip flaps operate in one of three modes; deployed during shutdown, in plane during normal operation, and position control during start-up until electrical synchronization is achieved. Position control is also used to limit the power production to 350 kW (maximum continuous rating of the major driveline components) in wind velocities over 35 mph up to shutdown at 50 mph.

Microprocessor Controller: The microprocessor based controller represents an integrated approach to system control. The four primary elements of this system are:

Data Display & Logging: All the operating parameters of the wind turbine are continuously updated and displayed on a large screen CRT terminal. This display serves to replace a large number of meters and indicators normally found on generator control systems. The extensive use of visual attributes, enhances the readability of operating data, calling attention to improper conditions. The remote control printer console (TTY) provides hard copy "LOGS" of the operating parameters every hour or as requested (Figure 2). This terminal also provides the means for entering supervisory commands. Certain types of alarms can be cleared from the TTY remote from the wind turbine station if so equipped. Detailed alarm messages are printed with the exact time of day and date of an alarm condition.

Supervisory Control: These routines schedule the operation of the wind turbine based on commands, wind conditions, alarms, etc. Machine start, run up, synchronize and shutdown sequences are also performed by the supervisory logic.

Machine Control: This includes the control of azimuth (yaw) position, speed/acceleration, synchronizing and power. Direct digital control used in these routines offers the advantages of flexibility, speed and accuracy. Parameters may be modified by WTG, Inc. as required for specific applications.

Machine Protection: A comprehensive alarm program included in the control software duplicates the functions of numerous protective relay devices as well as providing protection for many fault conditions generic to wind turbines which would otherwise not be available. Normal alarm response sequences (tripout, shutdown) are also contained in the logic of the alarm program.

Hardware backup protection of critical operating parameters is employed, providing baseline protection in the event of a computer malfunction. Elaborate fault diagnostics and error checking routines were designed into the control program, assuring that conditions leading to system faults are detected quickly and appropriate safety mechanisms can be brought into action.

All safety shutdown systems are inherently failsafe, in that aggregate component failures will not defeat shutdown actuators (tips and brakes). All elements in this system are mechanically stored energy devices. Faults resulting in a lockout relay trip automatically lead to a relay initiated emergency shutdown, which in effect interrupts the power to the shutdown devices needed to maintain an operating (run) condition. A coded alarm message is displayed on the CRT and TTY terminals providing a record of the fault(s) and facilitating diagnostics by operation and maintenance personnel.

#### MP1-200 OPERATIONAL EXPERIENCE

Beginning shortly after incorporation in the Spring of 1975, WTG Energy Systems, Inc. developed the MP-200 System design based on the design configuration of the Danish Gedser machine. The 200 kW size range was selected keeping in mind the engineering and manufacturing capabilities of the Company. It was believed at that time, that this intermediate size machine would have a marketing application in remote, diesel fired utilities where the cost of fuel would make the economic considerations feasible. Cuttyhunk Island, Massachusetts was selected for the site of the prototype MP1-200 unit as this small, diesel utility would be typical of the future applications for commercial wind generators.



In July, 1977 the MP1-200 prototype was interconnected to Cuttyhunk Island's grid of an installed capacity of 465 kW. It was noted in the initial operation of the MP1-200 that much developmental work was required to evolve a control system that would allow the machine to be compatible in performance, with small diesel/generator sets. A high gain governing system needed to be developed to operate stably with the existing diesel governors without modifying the diesel generator controls. Pitch control could not be used in this grid as its response time was not adequate to operate within the required frequency tolerances.

Over a two year period, a load modulation control system was developed utilizing a load bank with very fast switching action to regulate the effective load applied to the generator as part of a speed feedback control system. By the Summer of 1980, the Cuttyhunk machine was operating stably with the grid at penetration levels of over 100%, maintaining frequency regulation of less than  $\pm 0.5$  Hz (of power line frequency) in wind speeds of up to 40 mph. Power variations when operating on line can be maintained within  $\pm 10\%$  of nominal. At this time the MP1-200 has generated over 2,500 electrical hours into the Cuttyhunk grid.

The prototype has provided us with valuable operational experience which has led to the upgrading of subsequent machines. Based on results from numerous tests and operational experience on the MP1-200, the yaw drive has been modified, a yaw brake system has been retrofitted, valuable experience has been gained with operating in a corrosive salt water environment, and the surface coating specifications have been updated.

An extensive load and stress analysis program was conducted on the rotor and tower system to experimentally verify the initial design assumptions. Data was compiled and analyzed for the rotor's in plane bending moments, flapwise bending moments, low speed shaft bending and torsion, tower tension and torsional stresses, and the natural frequency calculations were verified experimentally. The theoretical performance calculations correlated very well with original design data.

Discussions are presently underway with the Town of Gosnold to sell the output of the MP1-200 to the town. It is anticipated that a contract will be finalized by September, 1981, and the MP1-200 will no longer be used as a research tool, but will be a fully operational on-line power source.

## MP2-200 OPERATIONAL EXPERIENCE

In the late Fall of 1979, WTG Energy Systems, Inc. was awarded a contract by the Nova Scotia Power Corporation for the first commercial MP-200 System unit. The MP2-200 machine was delivered and installed by the Winter of 1981. The severe winter at the Wreck Cove site delayed the commissioning schedule, so that it was not until late February, 1981 that the MP2-200 first generated power into the Nova Scotia grid.

The following modifications from the prototype have been incorporated into the MP2-200:

The ribs and skin of the rotor are fabricated from 304 stainless steel to provide increased corrosion protection.

The tip flap area was extended to from 13.3% to 16.7% of the airfoil area to provide greater drag during shutdown, and a lower idle speed.

The tip flaps are centrifugally augmented to insure failsafe operation in the event of rotor overspeed without loss of hydraulic pressure.

Blade skin thickness was optimized using 22 ga. stainless steel at the tip, progressing to 16 ga. stainless steel at the root end.

The root end spar weldment was moved outboard to decrease the bending moment and lower stresses transferred through the weldments.

Corrosion protection was improved on surface finishes.

The machine cabin and spinner were redesigned to provide greater access to machinery, and a tighter drive train enclosure.

Dual high speed shaft braking systems were incorporated.

The thermal rating of the generator was increased to compensate for peak power production approaching 400 kW on the prototype.

A complete manual control panel within the machine cabin was included.

Software modifications to permit tip control to replace load modulation (load bank) for speed and power control functions.

A remote supervisory control terminal to provide remote operation and the facility to reset alarms.

The Nova Scotia Power Corporation machine is used at the Wreck Cove Hydro Plant to pump water a height of 40 feet from a lower elevation lake to the main surge lake. As the hydro plant operates with a head of 1200 feet, the effective power of the 50 HP pump is greatly amplified. Pending the success of this unit, it is proposed that this demonstration unit serve as a model for similar installations within the Nova Scotia Power Corporation grid.

At this time, the MP2-200 has operated in the grid less than 100 hours due to schedule delay. The schedule presently calls for the wind generator to be in full production by mid-August.

#### MP3-200 OPERATIONAL EXPERIENCE

As the Nova Scotia Power Corporation unit was nearing completion of fabrication, WTG Energy Systems, Inc. received a contract to furnish Pacific Power & Light Co. with the MP3-200 for their Whiskey Run location. The fabrication and delivery of this machine was singularly unique in that the order was received the second week in September and the final shipment left the plant on December 16th of that year. The length of time from receipt of order to delivery was 14 weeks. The first on line operation of the MP3-200 occurred the third week of January, 1981, four work weeks after delivery.

Pacific Power & Light Co. plans to use this unit as a research tool, in cooperation with WTG Energy Systems, Inc. to "increase the knowledge of wind machine operation, wind turbine grid integration analysis and design features that impact allowable energy capture". Specific areas of study include power quality analysis, performance analysis, power dynamics, aerodynamic and airflow disturbance and control and dispatch strategies.

As of this date, the MP3-200 has been formally turned over to Pacific Power & Light and is approaching 500 hours of routine on line operation.

#### MP-600 SYSTEM DEVELOPMENT

Recently, WTG Energy Systems, Inc. received a contract to develop the detailed design of a 600 kW machine suitable for a commercial windfarm application. The final report will be submitted this week.

The MP-600 System is based on the MP-200 Systems experience and consists of a 125 foot rotor diameter mounted on a 115 foot tower. A 1000 HP transmission with a 48:1 gear ratio will drive a 750 kW, 4160 VAC generator. Details of this unit are summarized in the MP-600 System Wind Turbine Specifications.

Pending approval of the detailed design, production of this unit is scheduled to begin in the Fall of this year.

## CONCLUSIONS

### Systems Design

The rotor on the MP1-200 has successfully sustained  $5 \times 10^6$  completely reversing cycles, verifying conservative high-cycle fatigue criteria.

Improvements have been made in areas of high local stress concentrations providing additional assurances of "infinite life" fatigue considerations.

The protection and control system has proved to be a reasonable, cost effective approach.

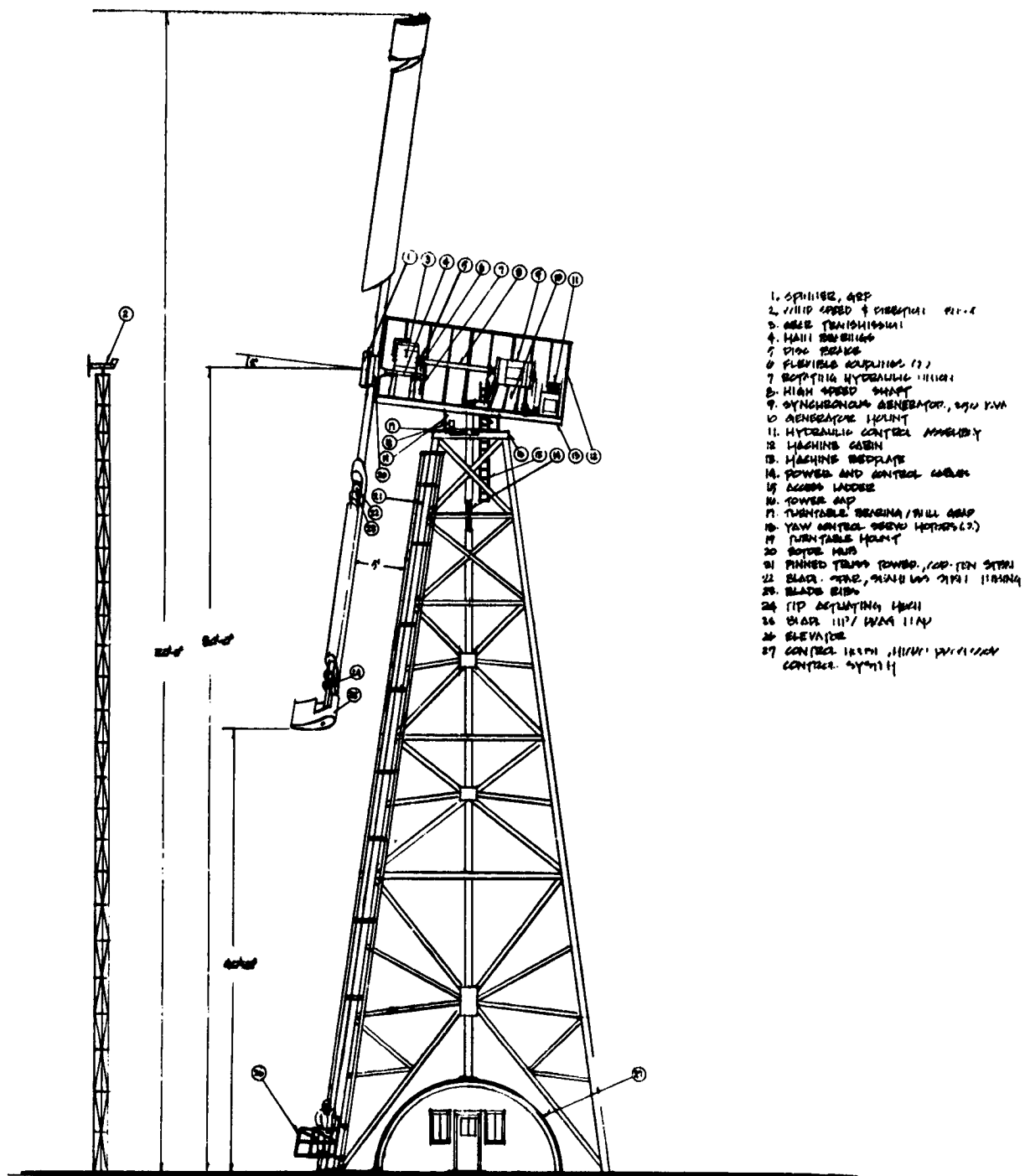
None of the MP-200 Systems have encountered a major component failure.

### Marketing

The marketplace has not verified our initial projections. Our two production units have both been purchased by "infinite bus" utilities, not remote diesel grids. We believe a cooperative relationship between the utility industry and "third party" investors will develop as the major marketplace for commercial units. The MP4-200, scheduled for installation in New England later this year, was purchased by such an investment group. In fact, the support of a major "third party" investment group has been critical to the development of the MP-600 unit.

However, our initial market assessment may develop at some future date. The international markets appear to be increasingly aware of our progress, namely, those remote, isolated diesel utilities. To quote from a recent study: "The WTG machine has the advantage that it has been specifically designed for isolated island environments and in fact has operated on an island ... for several years".

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MACHINE STATUS PRINTOUT

MP3-200 WIND TURBINE GENERATOR STATUS PRINTOUT

DATE: 041 TIME: 13:39

OPERATION MODE: AUTO RUN - ON LINE

COMPUTER ERROR CODE: 0000

ALARM STATUS: CLEAR ALARM CODE: 000.00

WIND VELOCITY: 24.2 MPH WIND DIRECTION: 198 DEG.

AVG. WIND VELOCITY: 23 MPH AZIMUTH POSITION: 198 DEG.

CABLE TURNS: 1 CW

LINE VOLTS (1-2): 494 TURBINE VOLTS (1-2): 494 TURBINE AMPS(1): 180

(2-3): 493 (2-3): 493 (2): 185

(1-3): 494 (1-3): 494 (3): 175

KILO-VOLTAMPS: 154 POWER FACTOR: .89 LAG KILOWATTS: 137 OUT

KILO-VOLTAMPS REACTIVE: 78 OUT

MILL FREQ: 60.01 HZ GEN. SPEED: 1201 RPM GEN.TEMP.: 30 DEG.C

\*\*\*\*\* ALARM \*\*\*\*\*

TYPICAL ALARM PRINTOUT

ALARM STATUS: CURRENT

ALARM CODE WORD: 000.20 (HYD.)

COMPUTER ERROR CODE WORD: 0000

MODE: EMERGENCY SHUTDOWN - LOCKED OUT

DATE: 041 TIME: 13:44

SUPERVISORY  
COMMAND MENU

KEYIN CODES: SE - SUPERVISORY ENABLE SS - SUPERVISORY STOP

ES - ENABLE SYNCHRONIZATION DS - DISABLE SYNCHRONIZATION

SD - SET DATE ST - SET TIME

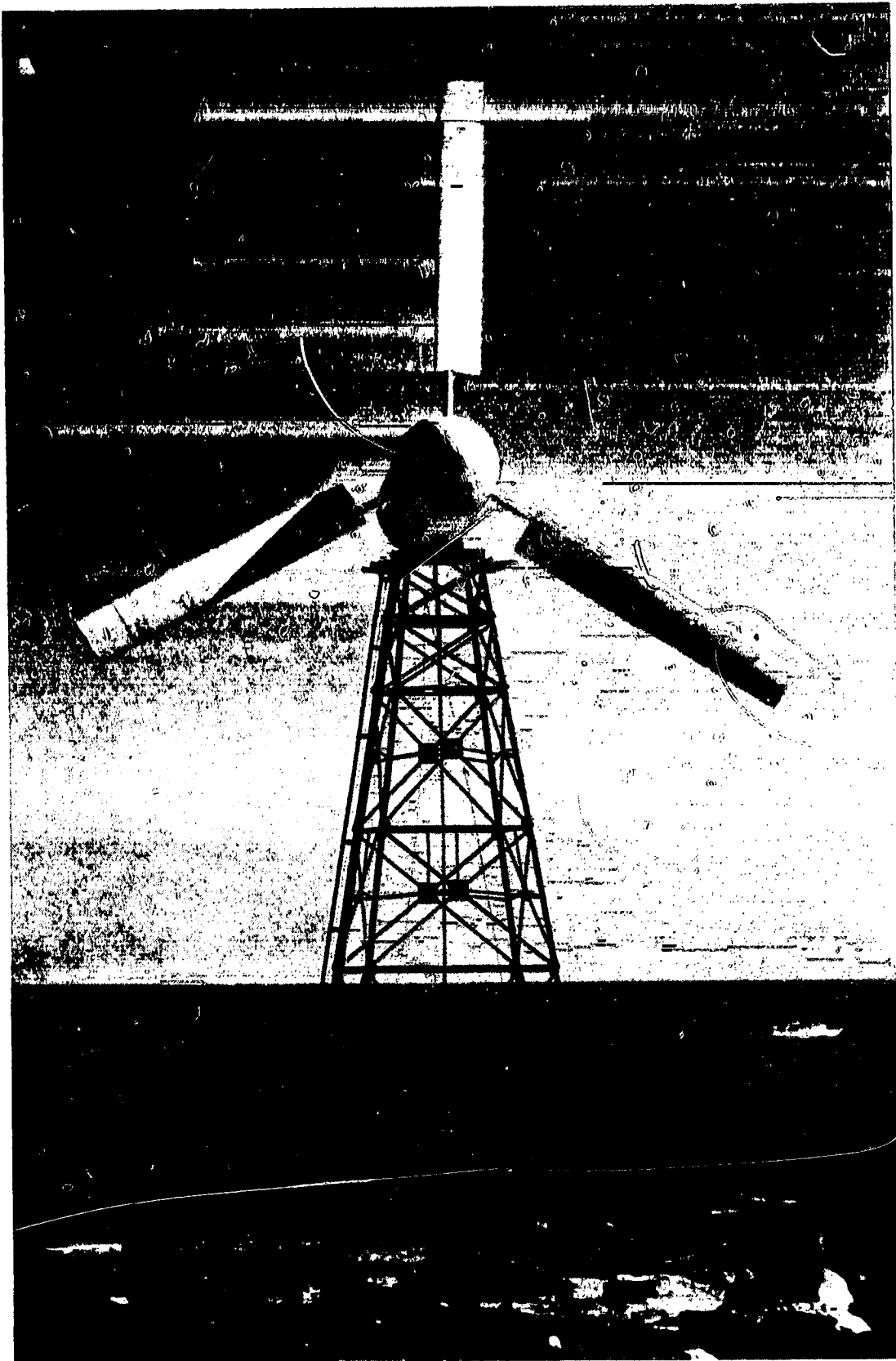
CA - CLEAR ALARM PS - PRINT STATUS

SP - SET POWER

ENTER 2 CHARACTER CODE FOLLOWED BY THE RETURN KEY. BELL INDICATES

THE ENTRY WAS NOT ACCEPTED. TRY AGAIN.

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MP1-200 WTG Energy Systems, Inc.  
Cuttyhunk Island, MA.

ORIGINAL PAGE  
BLACK AND WHITE PHOTOGRAPH



MP2-200 Nova Scotia Power Corp.  
Wreck Cove, NS



ORIGINAL PAGE  
BLACK AND WHITE PHOTOGRAPH



MP3-200 Pacific Power & Light  
Whiskey Run, OR

QUESTIONS AND ANSWERS

M. B. Rose

From: A. Saunders

Q: Theory indicates that yaw braking for 3-bladed props should be minimal. It would appear you have found this not to be true.

A: *Without an exact point of reference, it is difficult to gauge the yaw moment. On our 200 Kw series, this moment is on the order of 20,000 ft lbs max, 5,000 ft lbs typical.*

From: A. Saunders

Q: Can your high speed brakes bring the rotor to a stop from a full power wind velocity?

A: *There are two independent high-speed brakes. Either will stop the rotor in a full power wind. Both brakes will stop the rotor in less than 3 revs.*

From: Anonymous

Q: Do you keep a minimum load of the Island diesel at all times, or do you run stand-alone without any diesel back-up at Cuttyhunk?

A: *It is possible to run the town completely with the wind generator and this has been demonstrated. However, the WTG normally allows the diesels to "idle back."*

From: J. S. Wood, Jr.

Q: What was the cost of site work at Whiskey Run and why was it so high? What is the cost of the wind turbine and the tower at Whiskey Run?

A: *WTG Inc. is not responsible for the cost of installation and site preparation. The cost of the wind turbine alone, excluding expediting costs, was around 400K.*

From: S. Hightower

Q: What would be the cost of the 300 Kw machine sold to Pacific Power and Light if one were to buy the next unit?

A: *This figure may be around 420K not including the installation and site work.*

M. B. Rose (continued)

From: G. G. Biro

Q: Is the machine assisted with outside power? If so, what are the energy requirements?

A: *Yes, approximately 15 kva of auxiliary power is required. Typical daily auxiliary energy use is around 10 kwh (for machine requirements only).*

From: G. G. Biro

Q: What is 1) the initial cost, 2) the operating and maintenance costs and 3) the overall efficiency of the advanced type machine?

A: *It is too early to project the initial and the operating and maintenance costs. The overall efficiency is CP max approximately .39 from rotor to generator terminals.*

From: A. S. Jagtiani

Q: 1) What is the operating and maintenance cost on an annual basis?  
2) What is the energy rating at certain wind speeds?  
3) The supporting steel tower can withstand what wind speed?

A: 1) *This cost is dependent on the customer.*  
2) *200 kw at 30 mph,  $\geq$  350 Kw max at 40 mph.*  
3) *Lattice tower: 150 mph with 2 in. of ice.*

From: G. G. Biro

Q: What are the response times for cut-in and cut-out at high and low winds?

A: *Cut-in: from command entry to contact or closure - 1.5 min typical to 10 min maximum.*  
*Cut-out: Normal stop -  $< 3$  revs, emergency stop -  $< 1.75$  revs.*

LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Current Large Wind Turbine Systems

Session Chairman - V. J. Woyers (NASA LeRC)

"Development Tests for the 2.5 Megawatt Mod-2 Wind Turbine Generator"

J. S. Andrews

J. M. Baskin

(Boeing Engineering & Construction Company)

"Test Status and Experience with the 7.5 Megawatt Mod-2 Wind Turbine Cluster"

R. A. Axell

H. B. Wood

(Boeing Engineering & Construction Company)

"Mod-2 Wind Turbine Project Assessment and Cluster Test Plans"

L. H. Gordon

(NASA LeRC)

"Status of the 4 MW WTS-4 Wind Turbine"

R. J. Bussolari

(Hamilton Standard Division of United Technologies)

"The 80 Megawatt Wind Power Project at Kahuku Point, Hawaii"

R. R. Laessig

(Windfarms, Ltd.)

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DEVELOPMENT TESTS FOR THE 2.5 MEGAWATT MOD-2  
WIND TURBINE GENERATOR

J. S. Andrews and J. M. Baskin  
Boeing Engineering & Construction Company  
P.O. Box 3707, Seattle, Washington 98124

**ABSTRACT**

The development of the 2.5 megawatt MOD-2 wind turbine generator has included an extensive program of testing which encompassed verification of analytical procedures, component development, and integrated system verification. The test program was to assure achievement of the thirty year design operational life of the wind turbine system as well as to minimize costly design modifications which would otherwise have been required during on site system testing. Computer codes were modified, fatigue life of structure and dynamic components were verified, mechanical and electrical component and subsystems were functionally checked and modified where necessary to meet system specifications, and measured dynamic responses of coupled systems confirmed analytical predictions. It is clear that the importance of developmental testing has been demonstrated through the successful MOD-2 acceptance testing.

**INTRODUCTION**

The design of the MOD-2 wind turbine generator began in August, 1977 with final design being completed two years later in June, 1979. During this period, numerous wind tunnel, material and component development tests were conducted to support the concept, preliminary and detail design phases of this program. In conjunction with the fabrication phase and prior to first rotation, integrated system testing of critical components were conducted with the objective of design verification. These tests were planned so as to verify the function and dynamic characteristics of the components in an operating system.

This paper will describe the development tests and the impact that the test results had on component and system development. The MOD-2 wind turbine was designed using state-of-the-art materials and manufacturing techniques to reduce the development technical risks and eliminate expensive component development tests. Even with this conservative philosophy, the following additional tests were required; (1) wind tunnel tests to verify analytical load prediction models and aerodynamic configurations, (2) material testing to extend fatigue allowables data for steel to  $10^8$  cycles, (3) component tests to verify buckling, fatigue and operational characteristics to meet 30 year life and, (4) integrated system tests to verify component design in a dynamic operating environment.

The MOD-2 is a 2.5 megawatt wind turbine generator designed for 30 years life. The 300 foot rotor is made of a hollow welded steel

shell on a steel spar framework. The rotor also teeters at its center using elastomeric bearings, and has partial span hydraulic pitch control to regulate power output. The drive train, located in the nacelle has a "soft" quill shaft which is integrated with the pitch control system to regulate power quality and reduce oscillatory loads in the gearbox and synchronous generator. The nacelle is mounted on top of a cylindrical steel tower cantilevered from a concrete foundation which places the rotor hub at 200 feet above the ground level.

## WIND TUNNEL

It was recognized early in the conceptual design phase of the MOD-2 program that wind tunnel testing was necessary to obtain data for verifying the MOSTAS computer codes used for the determination of rotor blade design loads as well as being used for coupled dynamic analysis of a soft-tower wind turbine system. The test program which was subsequently conducted had several secondary objectives, in addition to the primary objective stated above. Included were (a) the comparison of fixed and teeter hinged rotors, and (b) the assessment of a rotor utilizing a controllable tip (as opposed to full-span) for providing rotor power control.

A 1/20 mach-scaled model of the MOD-2 WTS as shown in figure 1 was designed and fabricated for testing in the Boeing-Vertol 20 x 20 ft. V/STOL wind tunnel. The first model was designed to provide both hingeless and teetering rotor restraint, as well as incorporating full-span pitch control of the blades. Scaling of geometry, mass, stiffness and frequency were to be carried out in the model design. When it became impossible to scale nacelle mass (due to the weight of the model torque absorber system), compensating stiffness was added to the tower to obtain the proper frequency relationship between the tower and rotor rotational speed. When the evolution of the design progressed to the selection of a partial-span, blade pitch control, the model was modified to this configuration for a second test.

The operating wind turbine environment was simulated using a flow screen upwind of the rotor which had wire mesh density varying from tunnel floor to ceiling. The degree to which the design wind gradient was reproduced is shown in figure 2. Blade and tower bending and torsion loads were monitored throughout both tunnel tests.

The significant results of the MOD-2 wind tunnel test programs were as follows:

- a) The MOSTAB computer code was shown to provide a good prediction of power and of steady flapwise and chordwise bending moments. However, the MOSTAB program was found to underpredict the magnitude of alternating flapwise bending, and on the basis of the wind tunnel test results, a factor of 1.65 was incorporated into the program.

- b) The teetering rotor was shown to be superior to the hingeless rotor by reducing flapwise alternating moments approximately 50%.
- c) The dynamic characteristics of the soft tower concept, coupled with a dynamically scaled rotor, was proven over the operating wind speed and rotor rotation speed range.
- d) The MOSTAB and GEM-1 predictions of rotor performance were in agreement with test results for the tip controlled configuration.
- e) Performance of the tip controlled model compared well with that having full-span control.
- f) No deleterious vortex shedding characteristics of the cylindrical tower occurred throughout the test program.

## MATERIAL

All material testing, aside from quality assurance tests for material acceptance, resulted from requirements to assure the design was adequate for thirty years of operation. During its design life, a MOD-2 wind turbine rotor blade is expected to experience greater than  $2 \times 10^8$  load cycles. Thus fatigue is the major factor in the rotor design. No spectrum load fatigue data existed for the materials under consideration (ASTM-A588, A572, and A633) beyond  $1 \times 10^7$  load cycles. Therefore a fatigue test program was initiated early in the concept design phase that was to extend the fatigue data base to cover MOD-2 data requirements, i.e. the derivation of fatigue design allowable stresses.

The rotor is subjected to a spectrum of loadings, namely, thrust bending (flapwise) resulting from the variability of the winds with time, chordwise bending being basically the once per revolution variation of weight moment, and blade axial loading derived from centrifugal force and the once per revolution weight variation.

The MOD-2 rotor blade is an all steel structure, with transverse as well as longitudinal weld joints. All transverse welds on tension-fatigue designed surfaces have the weld reinforcement removed and have through-thickness inspections, both ultrasonic and radiographic. The installation of ribs and spars produce special welding and inspection considerations which ultimately affect the design fatigue allowables. The weld joints and their fatigue design allowables are the primary design considerations in sizing skin gages and thereby directly affect weight and cost.

The development of the design fatigue allowable stresses has been accomplished using the "preexisting crack" tolerance approach. This approach assumes the statistically determined worst possible defect which could escape detection, to exist when the system is put into service. The growth of the initial flaw (assumed to be a crack) is

described by a crack growth model which employs the stress intensity concept for characterizing the crack growth. The determination of the proper crack growth model to be used was accomplished by testing pre-cracked specimens under representative spectrum load conditions and correlating the crack growth results with the predictions from the several growth models that follow.

- (a) A retardation model which accounts for load interaction effects and considers all cycles to produce crack growth

$$(da/dn) = C(1-R)^n(K_{max})^m(K/K_{ol})^L$$

- (b) A threshold model which considers only those load cycles above the threshold to produce damage.

$$(da/dn) = 0 \text{ for } K \leq K_{th}$$

$$(da/dn) = C(1-R)^n(K_{max})^m, \text{ for } K > K_{th}$$

- (c) A combined effects model which accounts for both threshold and load interaction effects

$$(da/dn) = 0 \text{ for } K \leq K_{th}$$

$$(da/dn) = C(1-R)^n(K_{max})^m(K/K_{ol})^L, \text{ for } K > K_{th}$$

The fatigue test was carried on in two phases, the first one involved testing eighteen specimens, using variations of the design spectrum of the full-span pitchable blade. The second phase involved the testing of seven additional specimens to the tip-control load spectrum. Each specimen contained a surface flaw introduced by electric discharge machining. The specimen was then constant-amplitude fatigue tested to initiate a crack at the edge of the flaw (final size .05 inch deep by .25 inch long). The specimen was subsequently stress relieved to free the specimen of overload retardation effects that may have been introduced by the pre-cracking process. Each specimen was tested in a machine automatically controlled by computer, which permitted programming spectrum load cycles on a 24 hour, 7 day a week basis.

Analyses of the test results were accomplished by determining the best fit to each of the model predictions, figure 3. The combined model provided excellent correlation, where as the retardation model underestimated the lives of the long term tests, and the threshold model underestimated the lives of the short term tests.

The final crack growth model used for MOD-2 fatigue analysis, for all A grade steels is as follows:

$$(da/dn) = 0, \text{ for } K_{max} \leq K_{max}(\text{threshold})$$

$$(da/dn) = 3 \times 10^{-10}(1-R)^{2.4}(K_{max})^{3.0}(K_{max}/K_{ol})^2,$$

$$\text{for } K_{max} > K_{max}(\text{threshold})$$

FIGURE 4



## COMPONENT

Development tests were conducted to verify static strength, fatigue and operational characteristics of components to meet a 30 year life requirement. The following paragraphs will describe the component tests, test results and their impact on component design.

### Crack Detection

The crack detection system incorporated in the MOD-2 was designed to detect through thickness cracks in the rotor blade and shut the wind turbine system down prior to catastrophic failure of the rotor. The system basically pumps warm dry air through the blade envelope and dumps the air overboard at the inboard end, through an orifice. The flow through each blade orifice is monitored, and the difference between blade flows is an indication of the existence of another exhausting orifice, a through crack. The determination of the minimum length crack which could be detected was estimated using design parameters i.e. flow through a given sharp-edge orifice. However, the flow through a crack like orifice is at best difficult to predict, especially under various states of stress in the structure. To minimize false alarms, the critical leakage rate should be reasonably high, yet low enough to provide a comfortable margin between detection and structural failure. Fracture toughness testing was required to provide the data necessary for assessing the critical crack length for the MOD-2 blade material, which toughness had been assumed as being 125 Ksi $\sqrt{\text{in}}$ .

### Operational Test

A test was conducted to verify that the MOD-2 crack detection system possessed adequate sensitivity and stability to detect a given crack in one rotor blade as well as to detect malfunction of the system. Secondary objectives of the test program were to determine the maximum pressure capability of the blower, the power consumption of the equipment, and ability of the system to dry the air delivered to the blades.

Two 12,500 gallon tanks were used to simulate the air volume of the two rotor blades. Cracks in the blades were simulated by use of a manual valve and flowmeter on each blade simulator. The wind turbine crack detection system was located indoors and was connected to the blade simulator tanks, which were located out of doors.

During testing of the crack detection system, it was found that the blade orifice tubes had to be shortened in order to increase the air flow and thus increase the sensitivity of the system to air flow imbalance between blades. The system was able to detect malfunctions such as blower failure or air blockage. A 2 psi over pressure relief valve was incorporated to prevent over pressuring the blades, and a check valve was added to the dehumidifier outlet. The ability of the system to deliver dry air to the blades was confirmed. A system calibration procedure was established.

### Crack Flow Test

A crack flow test program was carried out on pre-cracked specimens .25 inches and .50 inches thick. The objective of the program was to experimentally develop a means of determining flow rate through a crack in a rotor blade under varying stress, pressure differential across the crack, and plate thickness for different crack lengths. Each specimen became the closeout panel of a rectangular flow chamber in which the pressure was varied by varying the inlet flow rate. Cracks of 9 inches and 12 inches were tested on the thicker panel, and cracks of 12, 18, and 24 inches were tested on the thinner panel. The test panels were clamped to the edges of the flow chamber so that the application of end loads on the specimen would produce uniform stress across the uncracked portions of the specimen. Gross area stresses were varied up to 9 Ksi and flow pressures (pressure differential across the crack) ranged up to 4 psi.

The state of stress affected the crack opening and thus the mass flow through the crack. The results of the testing indicated that the mass flow through a crack would follow the relationship:

$$\dot{m} = 2.7 \times 10^{-3} (t)^{-.25} (\sigma)^{1.65} (l)^{1.90} (\Delta P)^{.5}$$

### Fracture Toughness Test

The fracture toughness tests were conducted on two pre-cracked specimens fabricated from .25 in. and .50 in. thick ASTM-A572 grade 50 material to verify that the assumed toughness was greater than 125 Ksi $\sqrt{\text{in}}$ . Although the test material was not the MOD-2 rotor blade material (ASTM-A633 grade A, desulfurized) because of inavailability, it was felt that the differences favored the blade material as having higher toughness, and therefore the test results would be conservative.

The width of each specimen was 60 inches while the pre-crack was 24 inches long. The specimens were sized to give valid data up to 125 Ksi $\sqrt{\text{in}}$ . and conservative results above 125 Ksi $\sqrt{\text{in}}$ . Each specimen was instrumented with three crack propagation gages (Type TK040CPC 03-003), on the same side of the specimen. The first gage was located to one side of the crack tip by .08 and the second and third gages .08 inches from the first and second respectively. In this manner, a stable crack growth of 4.8 inches could be monitored.

During testing, the center portion of the specimen was enclosed in a styrofoam box which acted as a cryostat. Thus the test portions of the specimen was maintained at a temperature of -40°F, the minimum operating temperature for the wind turbine. The test load was applied at a rate such that a stress intensity of 125 Ksi $\sqrt{\text{in}}$ . would be reached in thirty seconds. The .25 inch thick specimen failed at a net area stress of 55 Ksi, which was greater than the guaranteed yield strength of 50 Ksi. The material toughness was well in excess of 225 Ksi $\sqrt{\text{in}}$ . The .50 inch thick specimen failed at a net area stress of 46.2 Ksi and an apparent toughness of 188 Ksi $\sqrt{\text{in}}$ . The average toughness of

206 Ksi $\sqrt{\text{in.}}$ , for the two specimen tests is well in excess of the value which was to be verified (125 Ksi $\sqrt{\text{in.}}$ ).

#### Crack Detection System Evaluation

The mass flow operation developed in the crack-flow test and the fracture toughness results were used to evaluate the ability of the crack detection system to detect cracks prior to reaching critical length. Figure 5 shows the relationship of crack-flow, as a ratio of detectable flow rate, to the number of days a detectable crack becomes critical. The relationship is for the blade station 360 which has the minimum time before a detectable crack becomes critical.

#### Rotor Rib Field Joint

The MOD-2 rotor blade has a field assembly splice at blade radial station 360 which attaches the blade mid-section to the hub through ribs that are welded to both skins and spars. The bolt attachment is symmetric about skin and spar. The joint is highly stressed under fatigue loading, and a test program was conducted to validate the joint for MOD-2 design. However, the results of this test provided additional substantiation for the crack growth model discussed under material testing.

The testing was carried out using an MTS (Material Testing System) test machine under the design fatigue spectrum of loads for the joint. The results shown in Figure 6 indicate good correlation was obtained between predictions and test results. The fatigue analytical model was validated and was used to design the field joint of the MOD-2 with a 30 year life.

#### Rotor Blade Static Buckling Test

The rotor blade has spars at two or three chordwise locations dividing the skin into long spanwise panels. Leading edge panels are curved in the chordwise direction, while those aft of the front spar are essentially flat. The panels on the airfoil upper surface are subjected to design limit compressive stresses during emergency shutdown in the outboard portion, and operating below rated wind with a gust in the inboard portion. The MOD-2 structural design criteria requires that initial buckling shall not occur at less than 1.35 times the design operating compressive stress.

Blade initial buckling stresses have been analyzed in the classical way, using the general equation,  $\sigma_{cr} = KE(t/b)^2$ . Buckling constant  $K$  is obtained from Boeing Design Manual DM 86B1 buckling curves for long flat or curved panels with simply supported edges. To verify the buckling analyses, and to validate their use for defining blade structural allowables, a bending test was conducted on a mid-span representative section of blade structure (see Figure 7).

The blade section included the field splice joint at station 360 and all structure outboard to station 780 inches. The specimen had a special bulkhead at station 780 to accommodate the load application fixture, while the inboard end was attached to a strong back. The loads at station 780 were applied in a combination of transverse shear and couple forces calculated to produce initial buckling in compression panels at stations 400 and 670 simultaneously. The specimen was instrumented with forty-two strain gages and twelve electrical deflection indicators. Test loads were monitored and controlled using three load transducers. Strain gage data from potentially critical buckling areas were monitored continuously during testing for any indications of initial buckling.

The results of the test have verified the conservative nature of the initial buckling analysis methods described above. The specimen was tested to 148% of the predicted initial buckling stress of one of the critical panels without buckling. The test results are summarized in the table below.

TABLE 1  
COMPARISON OF TEST DATA  
WITH PREDICTIONS OF INITIAL BUCKLING STRESS

<u>Blade Station</u>	<u>Analysis</u>	<u>Test</u>
	Initial Buckling	Maximum Measured - Test Stress
400	12,480 psi	18,500 psi
670	8,350 psi	11,220 psi

The conservative nature of the blade buckling analyses, as established by the static test, has validated their use as part of the wind turbine system blade design procedure.

#### Rotor Spindle

The spindle test program was performed to substantiate the structural integrity of the rotor blade spindle and its supporting structure. The design requirement to rotate the blade tip section resulted in complex structural load paths surrounding a spindle bearing structure. A complex finite element stress analysis was performed to evaluate this structure.

The test program objectives were:

- (a) To validate the analytical means for predicting the deflection and internal stresses of the spindle and supporting structure.
- (b) To define the areas of high local stresses in the spindle and supporting structure, which occur during normal operating

conditions of the wind turbine.

(c) Validate the operation of the pitch control system

The tests were performed by mounting the spindle section of the blade in a cantilevered position and applying combinations of flapwise and chordwise loads selected to produce one full life of fatigue damage on both the upper and lower blade surfaces. The test specimen included all blade structure between spanwise stations 1144 and 1360. The pitch actuator and supporting hydraulics were also included. Specimen test loads were imposed by a series of hydraulic actuators connected to the outboard end of the specimen through a rigid adapter fitting. A schematic of the test setup and the loads applied are shown in Figure 8 and a photo of the hardware and general testing arrangement appear in Figure 9.

Strain, deflection and applied loading data were recorded for all test conditions. The instrumentation consisted of 73 strain gages, 12 deflection transducers, 7 load cells, and one angular potentiometer.

All test objectives were achieved. The design lifetime (30 years) was demonstrated and good correlation was obtained between analytical stress predictions and measured stresses. The areas of high local stress were identified by analysis and confirmed by test (see Figure 10). No additional high stress areas were detected, and all margins of safety in the critical areas were equal to or greater than predicted.

#### Pitch Control Testing

Pitch control system testing included the use of the spindle fatigue test specimen as a means to functionally test the hydraulic swivel in the blade-tip pitch control system. The swivel is that portion of the hydraulic supply that provides the connection between the fixed portion of the blade at station 1249 and the tip actuator. The swivelling motion is from a tip position of  $-5^{\circ}$  to  $+94^{\circ}$ . The testing of the swivel joint included simulated startup, operate, and shutdown blade-tip pitch action as well as dithering for extended periods of time. During the spindle fatigue test, the control system was active and was used to pitch the tip section to operating or critical shutdown load positions ( $5^{\circ}$  or  $+28^{\circ}$ ). It was also used to maintain a given pitch position of the tip during the imposition of the time varying test loads. The control system held the pitch position to  $\pm 1.0^{\circ}$  under load application, thereby validating its design stiffness.

In order to develop and check out proposed changes in the pitch control system, open and closed loop frequency response tests were performed on the cyclic load test hardware. The test hardware provided the proper pitch actuator hydraulics and simulated tip rotary inertia. The objectives of the test were to evaluate proposed changes and optimize control system parameters to guarantee a 1Hz frequency response and demonstrate required stability margins. Various control system changes were evaluated on a patch board to arrive at an improved control system. In particular, the beneficial effects of eliminating

the Butterworth filter, implementing forward loop compensation and closed loop hardware were demonstrated. The optimum servo-driver gain at  $0^\circ$  and  $15^\circ$  was also determined.

Computer simulation of the control system had demonstrated that frequency response must exhibit a gain of  $-3\text{db}$  to  $+9\text{db}$  at  $1\text{ Hz}$  and outer loop stability requires a gain of at least  $-5\text{ db}$  at  $180^\circ$  degrees phase shift. The transfer function data obtained from the improved pitch control system of the cyclic load test specimen satisfied these requirements. Hardware and software modifications were later implemented and optimized during system integration testing.

### Teeter Bearing

The rotor is connected to the drive shafting through a teeter hinge and its elastomeric radially (teeter) and axially (thrust) loaded bearings. The radial bearings react rotor thrust, rotor driving torque, and rotor dead weight loads. The axial bearings are basically to react rotor dead weight  $90^\circ$  after the radial teeter bearings accomplished this task.

### Qualification Testing

The first elastomeric teeter bearing was subjected to qualification tests by the manufacturer in order to assure bond quality and to obtain performance data.

The soundness of the bonds between rubber and steel shims as well as between rubber and hub structure was verified by rotating the inner hub  $\pm 15^\circ$  relative to the outer ring structure. This angular motion was 2.3 times the expected extremes of travel during bearing operation ( $\pm 6\frac{1}{2}^\circ$ ). The torsional stiffness of the teeter bearing was ascertained at  $-40^\circ\text{F}$  as well as at room temperature. The results of the stiffness tests indicated compliance with bearing design specifications.

### Fatigue Testing

The teeter bearings had been designed with methodology developed for much smaller bearings used in the helicopter industry, and those used in the oil industry that require application of low stress low motion design. Because of a lack of test data and experience on bearings of the MOD-2 size, as well as the fact that the life requirement was well beyond even helicopter experience, it was decided that a fatigue test was required. In addition, this test provided data for maintenance and inspection procedures. Spectrum testing for the  $200 \times 10^6$  cycle equivalent of the design life (30 years) would be out of the question since the operating rotational frequency is  $17.5\text{ cpm}$ . A review of the operating loads and teeter angle spectrum indicated that, at best, bearing testing with applied loads of rated drive torque loads in combination with a time varying rotor weight

load as well as a rotation to maximum teeter motion ( $\pm 6.5^\circ$  to the teeter stops) applied for  $2 \times 10^6$  cycles would expose the bearing to an equivalent 30 year life.

The test bearing was heavily instrumented, using 14 strain gages on the inner hub to measure tangential and radial strains. Thermocouples were located at 8 selected places in the bearing rubber as well as on the inner hub. Instrumentation on the load application arms, in conjunction with displacement transducers, were used to determine the torsional and radial spring rates of the bearing. The test set-up is shown in Figure 11.

Throughout the testing, the radial spring rate did not vary at all, and the torsional spring rate had reduced 7% by the end of the test, well below the 20% failure criterion set by the bearing supplier. Stabilized temperatures in the rubber were approximately  $150^\circ\text{F}$  without fan cooling, and  $135^\circ\text{F}$  with cooling. Design operating temperatures will be well below the no-fan cooling temperature because design operating teeter angles are of the order of  $\pm 2$  to  $\pm 2\frac{1}{2}^\circ$ , not the  $\pm 6\frac{1}{2}^\circ$  continuous oscillation sustained during the bearing fatigue test.

#### Hydraulic Reservoir

The hydraulic reservoir is a tank located on the low speed shaft, providing storage for the hydraulic fluid necessary to power the blade pitch control. The fact that it is located on the low speed shaft eliminates the need for a hydraulic slip ring. However, it did require a special type of attachment structure so that it maintains constant orientation with the fixed system. Thus fluid is extracted from the reservoir from a fixed part of the tank.

It was determined that an operational test was necessary to evaluate (a) fluid sloshing at various fluid levels, (b) air entrainment in the fluid and its effect on bulk modulus, (c) adequacy of the sealing system, (d) adequacy of the fluid quantity indicating system, and (e) adequacy of the venting system, fluid return, and pump intake provisions.

The test reservoir was a specially designed cylindrical 30 gallon tank having a clear acrylic plastic outer shell, which in turn was rigidly mounted to a rotating fixture (Figure 12). The axis of the reservoir and the rotation axis of the fixture were parallel and separated by 30 inches. The test reservoir contained a system of baffles mounted on bearings and weighted so that the baffles maintained an upright position during rotation of the outer shell and test fixture. The reservoir vent and pump supply tubes were attached to longitudinal baffles. The hydraulic circuit included a flow meter, circulating pump, and an accumulator for applying flow surges in the system return line.

Test data was primarily in the form of photographs, visual observations,

and tabulation of bulk modulus measurements. Observation of air entrainment and the lack of a quiescent sump for collection of water and dirt resulted in design changes to the production system. The production reservoir is now trunnion mounted, without internal baffles. A return line diffuser has been incorporated to reduce turbulence and aeration. The bulk modulus remained essentially constant throughout the test and fluid sloshing was within limits up to 20 RPM (operating RPM is 17.5).

### Gearbox, Back to Back Test

#### Fatigue Testing

The epicyclic gearbox selected for the MOD-2 utilized an existing design concept but its torque transmitting capability was improved by 200% and its new design life was thirty years. Because the capabilities extension was beyond the current state-of-the-art, a qualification test was deemed necessary to verify predicted performance parameters.

The selected test method was a back-to-back test in which two complete gearboxes and their lubrication systems would be connected in order to impose the high input torques of the operating wind turbine (Figure 13). The high speed output shafts were connected via way of a torsion bar, while the torque reactions were through the low speed shaft flanges, as both low speed shaft flanges were tied together. The torsion bar preload was varied throughout the test to provide simulated drive line power variations in operation. A drive motor was connected to the output shaft of one of the gearboxes, providing the rotational speed control. The gears of one of the boxes were strain gaged to monitor the tooth stresses throughout the program.

Table 2 provides the spectrum of operating conditions simulated in this test program. During the test program, it was determined that gear tooth bending stresses were well below AGMA predictions. Slight modifications to the first stage helical gears lead correction angle had to be made, and it should be noted that had a full load test not been conducted, such a deficiency would have gone unnoticed. Direct measurements of gear train efficiency, gearbox breakaway torque, noise levels and vibration characteristics were made throughout the test.

As a result of the back-to-back test program, the fatigue rating of the gearbox was substantiated up to 155% of design rated torque.

#### Vibration Survey

Running of the gearbox at zero torque during the back-to-back load test, a rapid buildup of horizontal vibration at 1400 output RPM was experienced. The system ran smoothly up to 1800 RPM with the application of only 1% of rated torque. It was determined that the



gearbox third stage planet passage frequency was resonant with the test stand yaw/lateral natural frequency. At low torque levels, the third stage planets and sun of this gearbox are free to move off their rotating center, causing unbalance at the planet passage frequency.

The gearbox mount lateral stiffness was determined from subsequent tests. Analysis of the gearbox as installed in the MOD-2 nacelle predicted natural frequencies well in excess of 2600 RPM. Therefore no mount vibration problem at planet passage frequency was expected. This was subsequently confirmed in integration testing of the installed gearbox.

TABLE 2  
LOAD-ROTATIONAL SPEED SPECTRUM  
GEARBOX BACK-TO-BACK TESTING

<u>TORQUE (%)</u>	<u>RPM(%)</u>	<u>TIME (HOURS)</u>
0	50	1
0	100	1
15	100	1
45	100	1
75	100	10
110	100	10
155	100	100
0	130	0.5

## INTEGRATED SYSTEM TESTING OF COMPONENTS

### Pitch Control System

During preliminary design, it was recognized that a test program was necessary for the evaluation of the blade pitch control system, end to end, prior to wind turbine system evaluation in the field. The assembly of the nacelle, including the complete drive train and the nacelle control unit (NCU) was planned to be completed well in advance of the rotor. Therefore it was necessary to design and fabricate a rotor simulator to be attached to the first nacelle-drive so that the pitch control could be functionally evaluated against a rotor load. The rotor simulator also permitted the rotation of the drive system at various RPM to assess electronic control through the rotor slip ring and hydraulic system functions under centrifugal loading. A field test unit (FTU) provided the means to input electrical signals which would simulate data sensed by those wind turbine sensors to which the control system would respond (wind speed, rotor speed, and yaw position).

Normal and emergency shutdown as well as normal operations were simulated and several control system hardware deficiencies were observed: (a) a valve in the rotor hydraulic control manifold leaked, and (b) a control system servo valve malfunctioned. Subsequent redesigns

replaced both valves with more reliable components. All control system responses to simulated operating loads were verified.

#### Pitch Control Rotor/WTS

The pitch control system was ground tested on the rotor and later during system integration testing with the nacelle and tower. The ground tests with the rotor (rotor stand-alone) were performed with the rotor in cradle supports with the blade tips free to move. The objective of the rotor stand-alone tests was to demonstrate that the pitch system design modifications, introduced to resolve hydraulic and electrical anomalies uncovered during the rotor simulator tests, were properly integrated into the wind turbine system. These tests also provided the opportunity to test the pitch control system with final hardware modifications including actuators, spindles and blade tips. The dynamics tests included emergency feather rate, controlled rate, blade standoff and position error and frequency response tests. All pitch system test requirements were met during rotor stand-alone testing or illustrated by the frequency response test results shown in Figure 14.

The same series of pitch control system tests were repeated with the rotor installed on the nacelle, during integration testing. All system tests were successfully completed and compared favorably with stand-alone results shown in Figure 14.

#### Modal Survey

Modal survey testing of wind turbine systems and their components is an important part of the design and testing process. The modal survey is an effective way to insure that the wind turbine subsystems meet performance expectations.

After evaluating alternative testing techniques, it was concluded that the MCD-2 modal survey would be conducted with the rotor and nacelle installed on the tower in the operational configuration. The advantages were that the system modes and damping would be measured directly, including all coupling mechanisms which were hard to model.

The testing approach selected involved the use of a HP 5451B Modal Analysis System (similar to the one used for the modal analysis of MOD-0). The test technique involved impacting the wind turbine at a prescribed point with a 1000 lb. instrumented ram and recording the responses of fixed accelerometers. The impact load transient and the response signals were simultaneously recorded and fed into the HP 5451B MAS to determine mode shapes, frequencies, and damping. The overall technique is based on the use of digital processing and the Fast Fourier Transform (FFT) to obtain transfer function data and then use of a least-squared error estimator to identify modal properties from the transfer function data.

A specially designed 1000 lb. ram was instrumented with a force transducer in its head. The ram was swung from the gin pole used for MOD-2 erection and allowed to impact the blade tip. To insure a proper impact, the ram was constrained to follow a cable, through the center of the target disc.

To excite the significant modes of interest, the impact force must be of sufficient magnitude and duration. The ram was calibrated before the modal survey by varying the stiffness of the ram impact head (interchangeable foam rubber pads) and varying the swing length to develop approximately 1000 lb. with 200 ms duration.

The modal frequencies and damping resulting from the modal survey are shown in Table 3. The data is a direct output of the HP 5451B Fourier Analyser System with the exception of chordwise bending, nacelle pitch and drive-train torsion modes which were determined by supplemental means.

The data gathered during the MOD-2 modal survey tests verified the achievement of required system design frequencies. In particular, the drive train, tower and blade modes were identified and shown to meet system frequency placement and separation. The measured damping provided assurance that design damping assumptions were reasonable.

TABLE 3  
MOD-2 MODAL SURVEY RESULTS

Mode	Freq. (Hz)		Damping (%)
	Pred.	Meas.	Meas.
Tower	0.14	----	----
Drive Train Torsion	0.46	0.45	----
Tower Bending Fore/Aft	1.24	1.23	1.0
Tower Bending Lateral	1.27	1.28	4.2
Flap Bending Sym.	3.09	3.30	0.35
Chord Bending Sym.	6.22	6.17	----
Flap Bending Antisym.	6.45	6.55	1.04
Flap Bending 2nd Sym.	7.71	9.6	0.78
Nacelle Pitch		8.23	

## SUMMARY AND CONCLUSIONS

A series of tests have been conducted in support of MOD-2 wind turbine component development. For the most part, these substantiated the soundness of the particular component design. Each test was conducted on a schedule such that the results could be incorporated into the design detail of the specific component. The objective of the test programs varied, but could be included in one of the following categories: (1) verification of analytical prediction methods, (2) provide data for design of the component, (3) verification of life

prediction, (4) verification of static strength capability, (5) assess critical load paths, and (6) functional verification. The component and integrated system tests described in this paper had one of or combinations of these objectives.

Component testing was vital to the development of the MOD-2 wind turbine system because the tests provided early visibility to design problems and provided the data required to develop sound design solutions. The design deficiencies brought to light by these tests were promptly corrected, thereby avoiding costly retrofits during the checkout and acceptance tests of the system. MOD-2 checkout and acceptance phases have proceeded on a faster schedule than anticipated, and is for the most part due to the component and integrated system testing described in this paper.

## NOMENCLATURE

C	= Constant
K	= Stress Intensity, Ksi
K <sub>max</sub>	= Maximum Stress Intensity of the Specific Load Cycle (Sum of Steady and Alternating Stresses), Ksi
K <sub>01</sub>	= Maximum Stress Intensity in the Spectrum of Stresses, Ksi
K <sub>th</sub>	= Stress Intensity Threshold (Stress Below Which Damage is Not Produced), Ksi
L	= Exponent
$\Delta P$	= Pressure Differential Across Panel, psi
R	= Stress Ratio, Minimum Stress/Maximum Stress
da/dn	= Crack Growth Rate in Inches/Cycle
l	= One Half of Crack Length, Inches
m	= Exponent
$\dot{m}$	= Airflow, in Cubic Feet per Minute (Std Conditions)
n	= Exponent
t	= Plate Thickness, Inches
$\sigma$	= Gross Area Stress in Plate, Ksi

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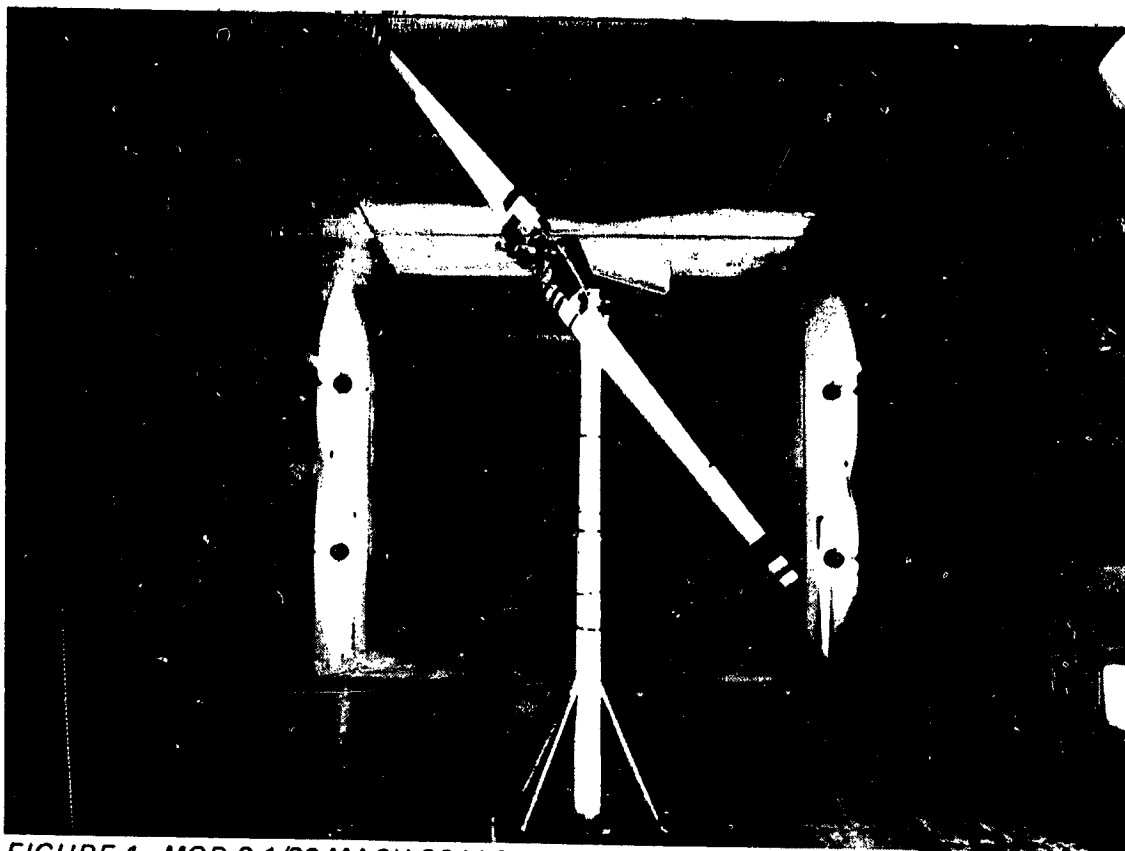


FIGURE 1. MOD-2 1/20 MACH SCALED MODEL IN BOEING V/STOL WIND TUNNEL

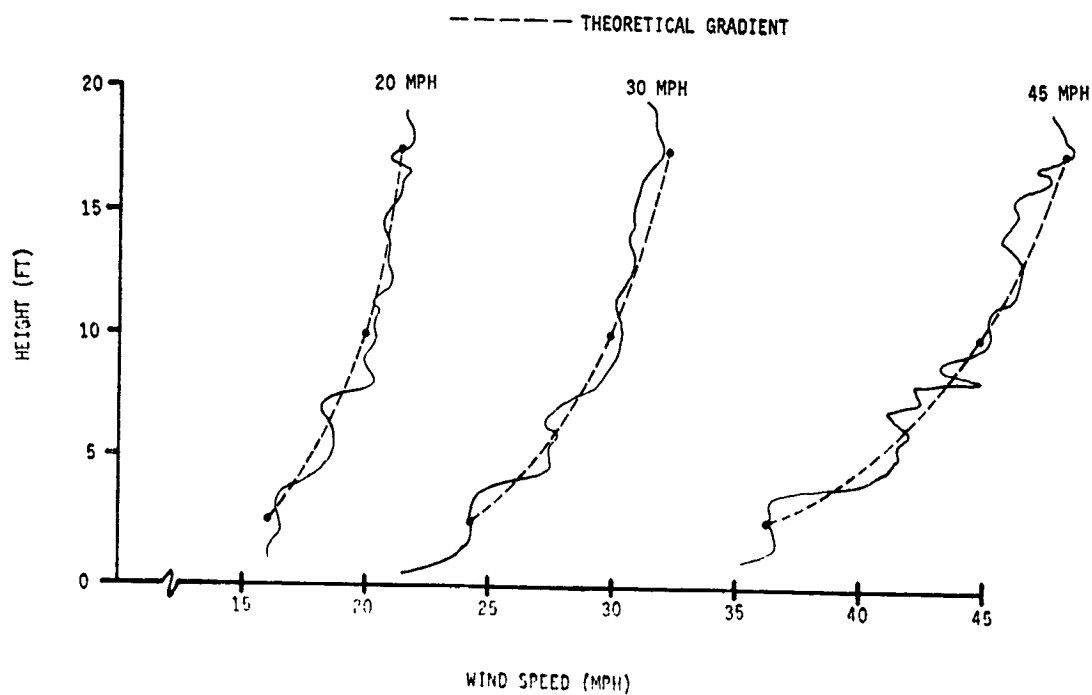


FIGURE 2. WIND GRADIENT SCREEN EVALUATION

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- Each bar represents a test data point
- Except as noted the test material was A533

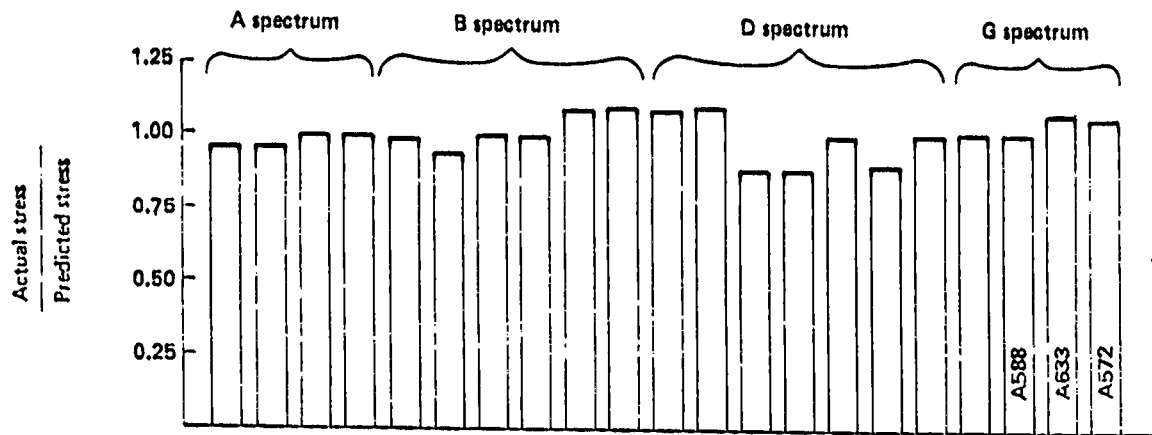


FIGURE 3. CORRELATION OF TEST AND PREDICTED RESULTS

- Model derived from spectrum load test results
- Model is good for all A grade steels
- Model applicable to all wind turbine spectra

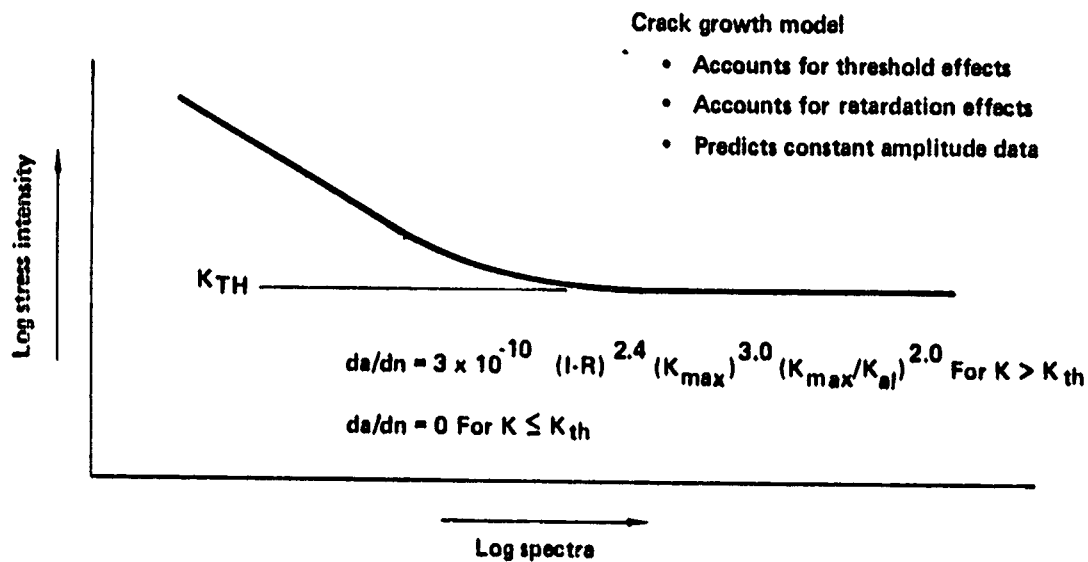


FIGURE 4. FATIGUE ALLOWABLE MODEL

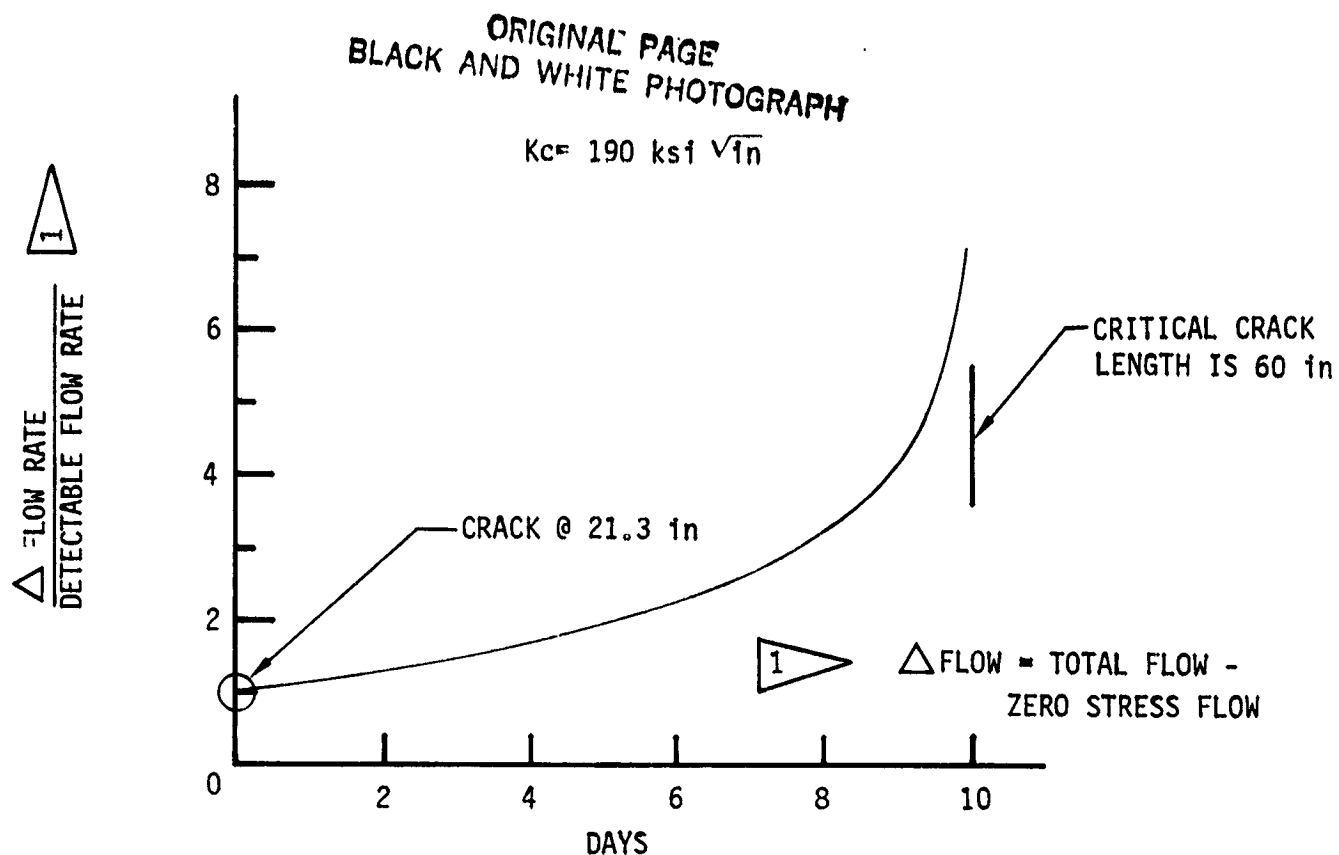
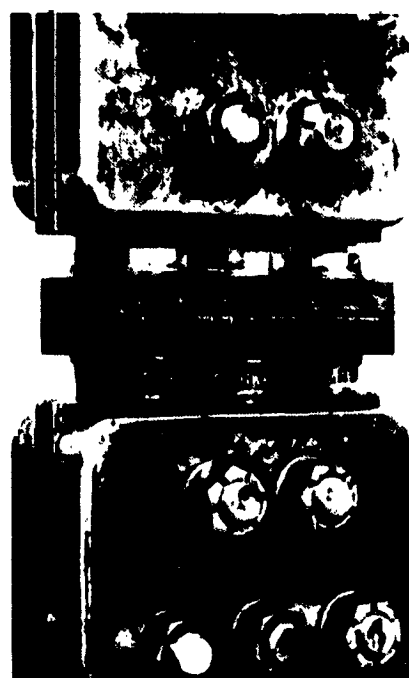
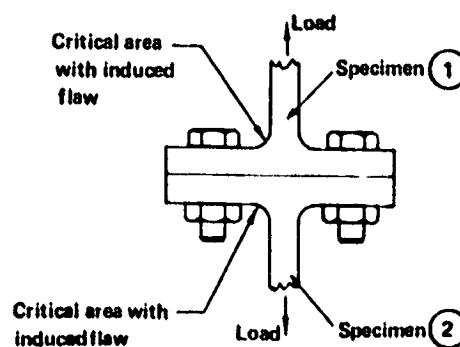


FIGURE 5. CRACK DETECTION SYSTEM CAPABILITY FOR MOD-2  
BLADE STATION 360 BASED ON  $\Delta$  FLOW



INSTALLATION  
IN TEST MACHINE



TEST DATA

	①	②
• Fillet area stress (psi)	18,000	18,200
• Initial flaw length (in.)	0.248	0.234
• Predicted fatigue life	17,000,000	17,000,000
	Cycles	Cycles
• Test Specimen Life	18,953,754	21,151,277
	Cycles	Cycles

FIGURE 6. ROTOR BLADE FIELD JOINT TEST

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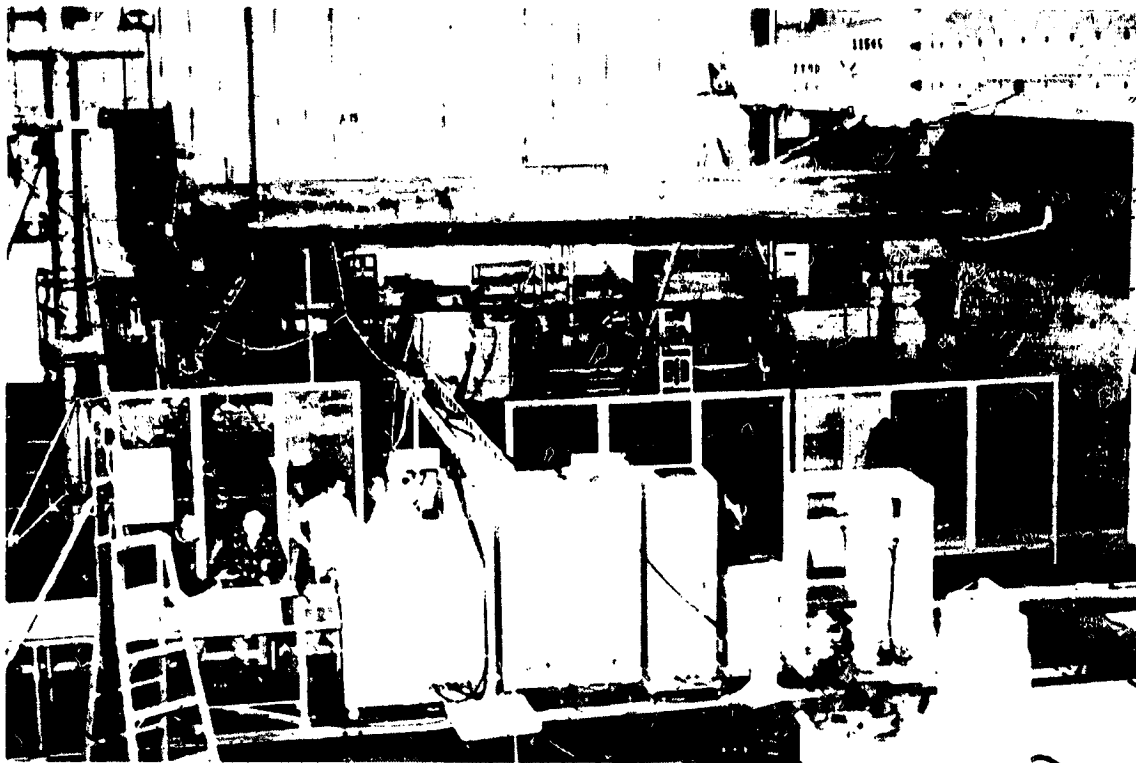


FIGURE 7. BLADE STATIC BUCKLING TEST

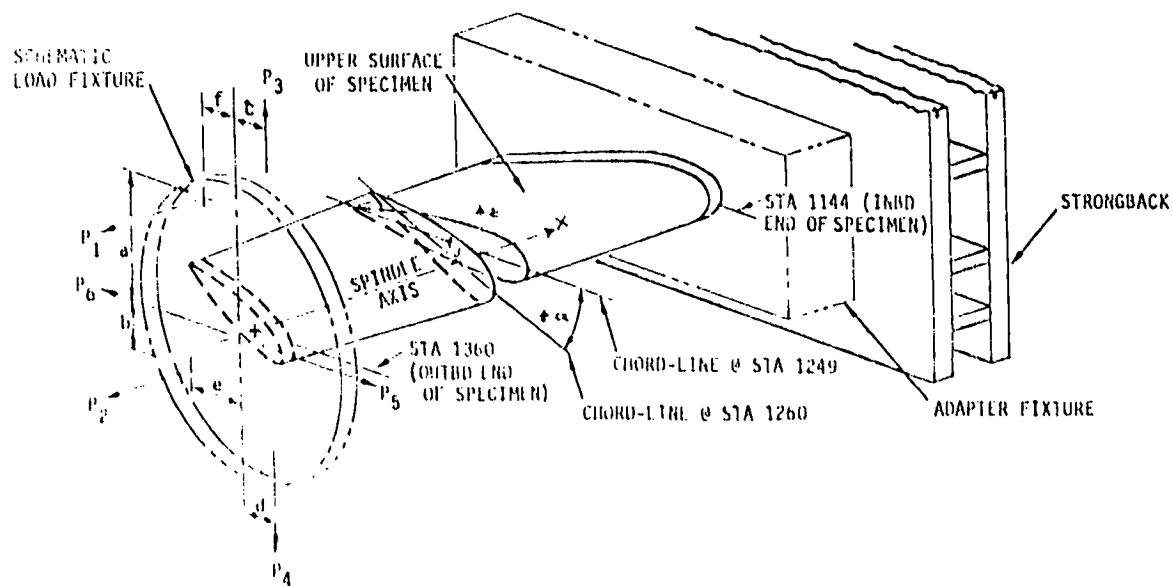


FIGURE 8. SCHEMATIC OF SPINDLE FATIGUE TEST SETUP



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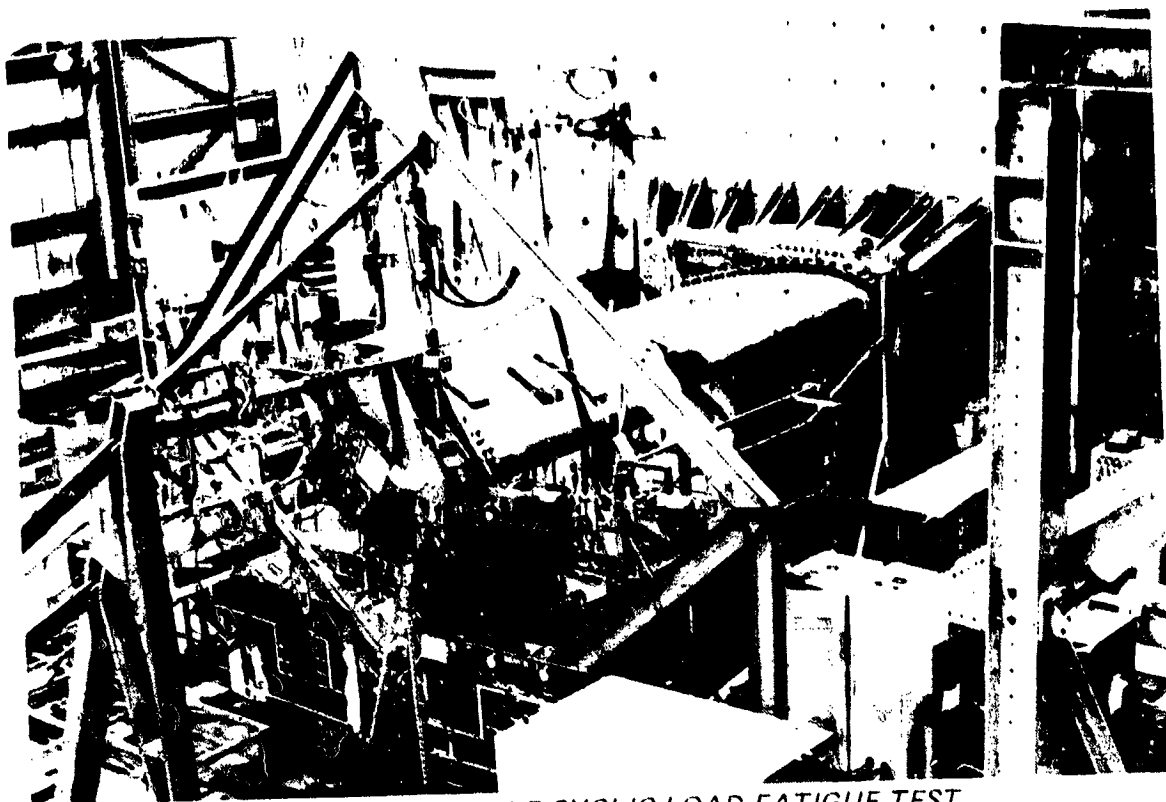


FIGURE 9. SPINDLE CYCLIC LOAD FATIGUE TEST

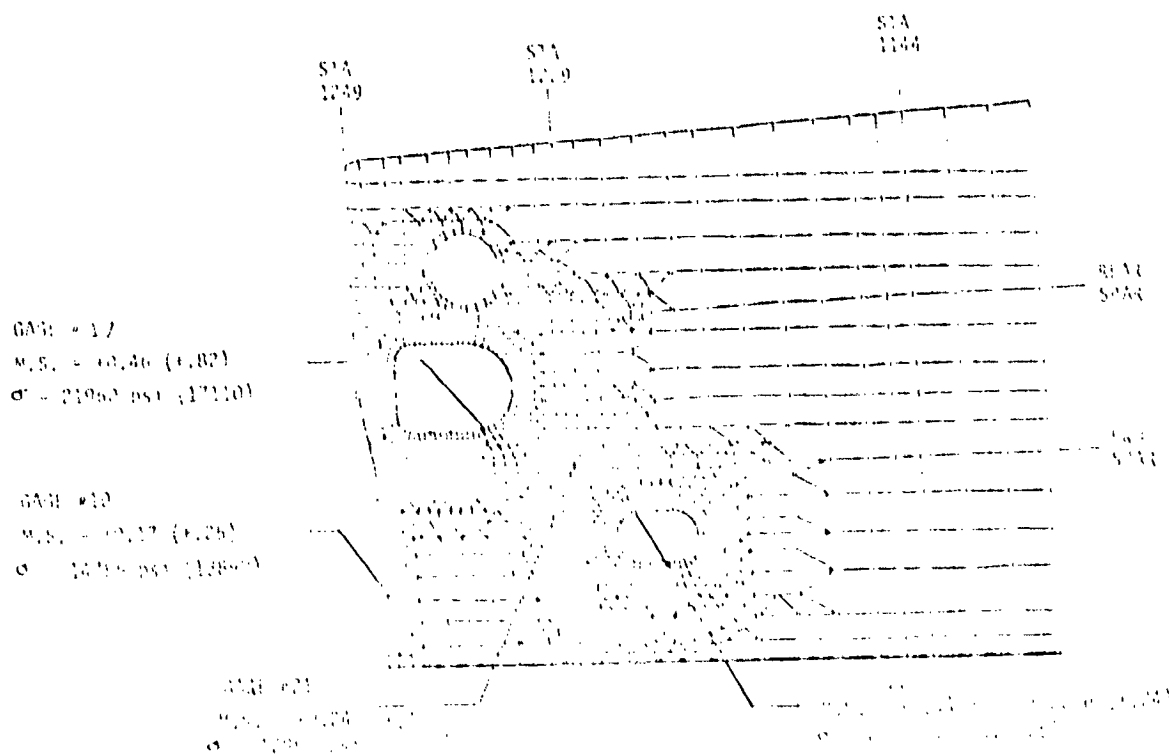


FIGURE 10. MARGINS OF SAFETY AT CRITICAL LOCATIONS OF TEST SPECIMEN.  
INBOARD SECTION, UPPER SURFACE COMPARISON OF ANALYSIS  
WITH (TEST)

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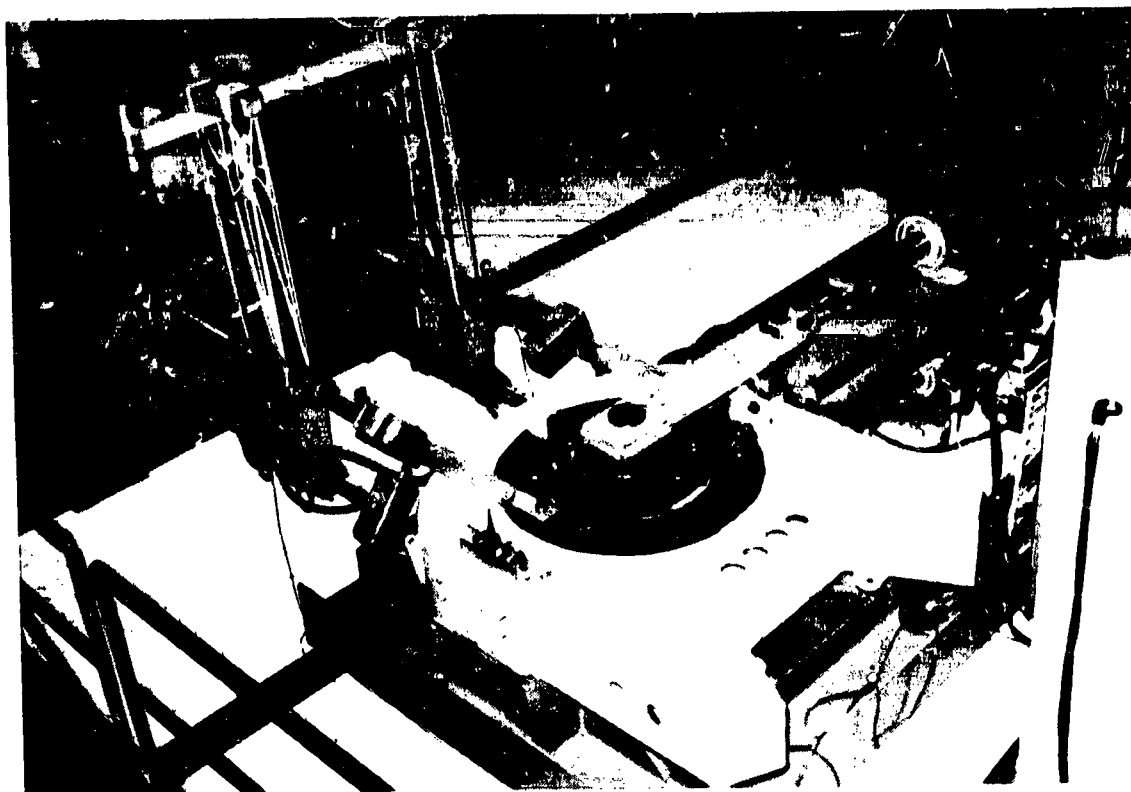


FIGURE 11. TEETER BEARING FATIGUE TEST

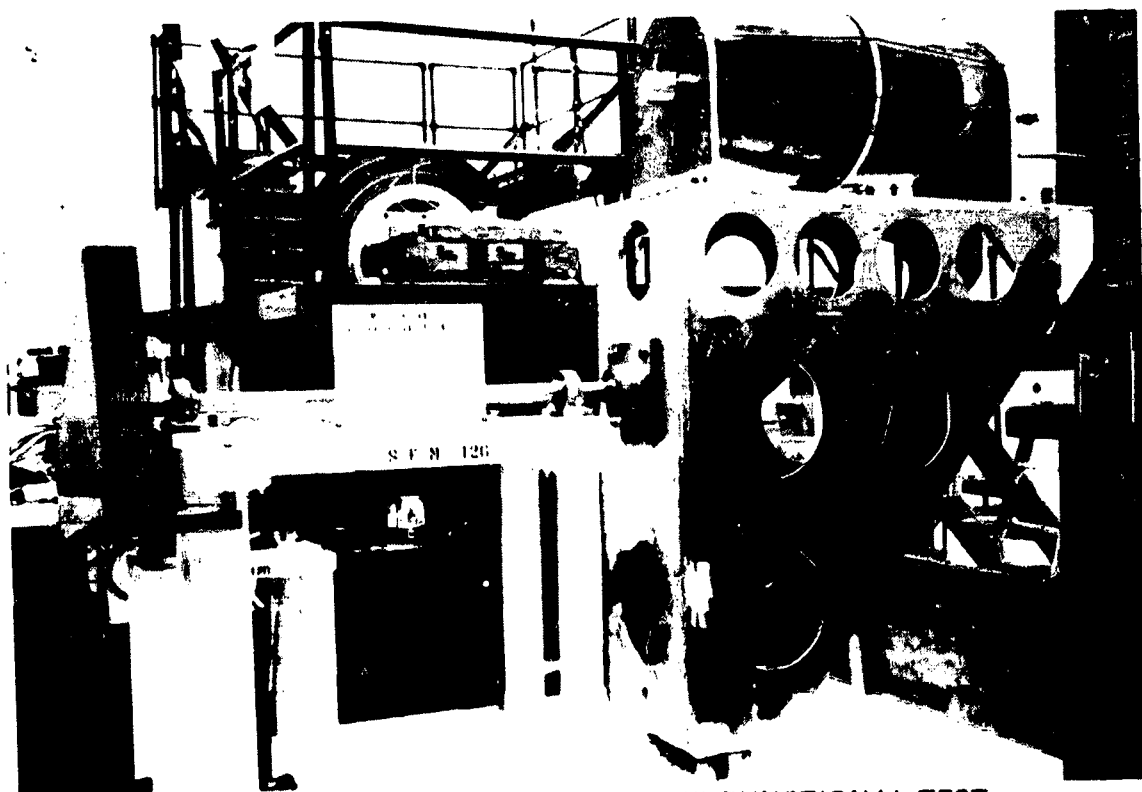


FIGURE 12. HYDRAULIC RESERVOIR FUNCTIONAL TEST

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FIGURE 13. GEARBOX BACK-TO-BACK TEST

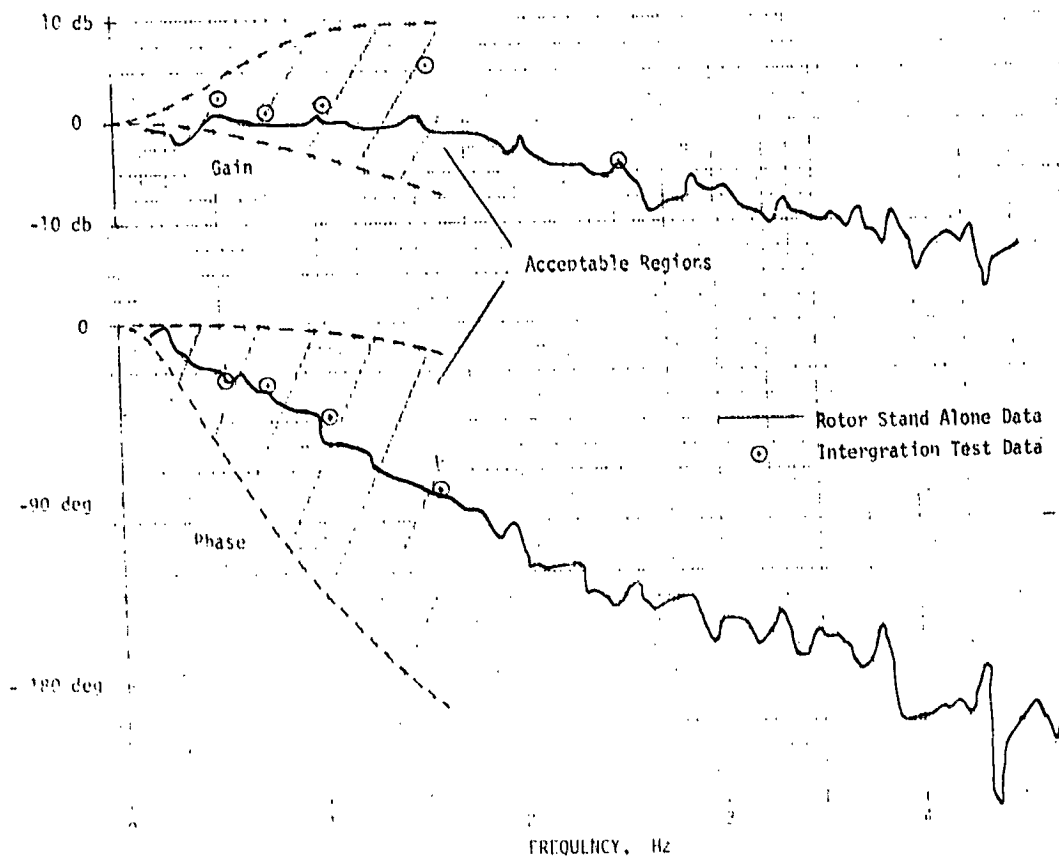


FIGURE 14. CONTROL SYSTEM RESPONSE TO INPUT COMMAND

## QUESTIONS AND ANSWERS

J. Andrews

From: A. Swift, Jr.

Q: Does the Mod-2 teeter mechanism teeter freely or is it spring loaded?

A: *It teeters freely. The teeter bearing has been designed for a very low radial stiffness in the teeter direction. From a frequency standpoint, this is close to zero but enough to keep oscillation low during shutdown.*

From: R. Simon

Q: Is the teetering mechanism on Mod-2 designed to handle strong decreases of wind with height?

A: *Yes, up to extreme winds of 138 mph with blade vertical, downwind of the tower.*

From: T. Andersen

Q: How are hydraulic connections made to a gimbaled reservoir without a rotating coupling?

A: *It has a rotating coupling under very low pressure.*

From: R. Barton

Q: Regarding the crack detector system, how do you detect the "same" size crack in each blade? The comparison system is blind to this occurrence (i.e. the difference in crack size is less than the detectable 21.3 inch length).

A: *You cannot detect the same size crack in each blade, but the probability of having this occur in each blade is very low.*

From: W. Lucas

Q: What is the "initial flaw size" used for fatigue analysis of welded joints and was the same flaw size used throughout the system?

A: 1) *0.25 x 0.05 inches in welds for analysis and 0.125 x 0.05 for inspection.*  
2) *No, the same flaw size was not used throughout the system. On some machined parts, the flaw size was smaller.*

From: P. A. Bergman

Q: With regards to designing for fatigue, would not an existing "cumulative damage" type of analysis be applicable to this problem?

J. Andrews (continued)

A: *Yes, if you had a SN curve out to  $3 \times 10^8$  cycles. But as I pointed out, it would take many many samples in order to establish the statistical SN allowable curve; and if you assumed it followed the retardation effect, you would over design the blade and it would be extremely heavy.*

From: R. C. Henson

Q: How frequently are crack tests made?

A: *At the beginning of each start up.*

From: T. Zajac

Q: Were environmental factors taken into account in fracture mechanics evaluation?

A: *Yes, by the selection of proper steel (i.e. deaeritized, no copper content).*

From: S. Rao

Q: Can you talk about the generating system and any associated problems/inadequacies?

A: *No problems. It is a standard synchronous generator.*

From: J. M. Medaglia

Q: How much of the Mod-2 structure is designed by fatigue rather than limit loads?

A: *The entire rotor except for large areas on the compression side, and local areas in the nacelle and tower. The entire drive train is designed by fatigue.*

TEST STATUS AND EXPERIENCE WITH THE  
7.5 MEGAWATT MOD-2 WIND TURBINE CLUSTER

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## ABSTRACT

On May 29, 1981, a ceremony was held to dedicate the 7.5 megawatt MOD-2 Wind Turbine Cluster located at Goodnoe Hills, near Goldendale, Washington. This paper presents a description of the development of that cluster, including site preparation and construction activities, preliminary test results and current status and future plans for the facility.

## MOD-2 SYSTEM DESCRIPTION

### MOD-2 Program Profile

The MOD-2 is a 91 meter (300 foot) diameter, 2.5 megawatt wind turbine system developed by Boeing Engineering and Construction Company (BEC) for the Department of Energy under direction of the NASA Lewis Research Center. The program started in August of 1977, first rotation occurred in November of 1980, and the first three units were completed by May of 1981. The basic objective was to design, fabricate, install, checkout, and deliver large megawatt-sized wind turbines which would be economically competitive with conventional power generating equipment operating in utility networks. The DOE-funded program is for four units of which three units have been installed as a cluster near Goldendale, Washington, and the fourth unit is being installed near Medicine Bow, Wyoming. The major milestones, as shown in Table 1, provide a chronology of program development.

### The Goldendale Installation

The three-unit installation at the Goldendale (Goodnoe Hills) site overlooks the Columbia River in a location well suited for capturing the prevailing westerly winds. This site has been designated as a national wind turbine test facility and will serve as a test bed for evaluating cluster arrangement and operations as well as for individual machine performance optimization, product improvement, and maintenance program development.

### The MOD-2 Machine

The MOD-2 program was initiated with several DOE/NASA specified ground rules which laid the framework for developing a new generation wind

turbine suitable for commercial production and installation. The primary requirement was to provide a viable alternative to conventional power generation systems. The design optimization and economic evaluation conducted during these initial program phases resulted in the configuration shown in Figure 1.

Studies of various rotor configurations led to the selection of a steel, upwind-oriented rotor with movable tip sections for controlling rotor speed and power output. Upwind orientation with positive, hydraulic yaw control is employed to minimize tower shadowing effects, rotor fatigue and noise, and to maximize energy capture by accurately controlling nacelle heading. Rotor weight, cost and complexity are reduced significantly by controlling the pitch angle of the outer one-third of each rotor blade rather than employing full span control (see Figure 2). The pitch control system hydraulic elements are physically located on the rotating low speed shaft and in the mid-blade near the tip joint, thus eliminating hydraulic slip joints and increasing system reliability. The rotor hub incorporates elastomeric radial bearings which allow the rotor to teeter within a range of  $\pm 6$  degrees. This feature significantly reduces fatigue loads thus permitting use of lighter, lower cost structure. The teetered hub arrangement is shown in Figure 3.

Unique aspects of the MOD-2 drive train include a "soft" quill shaft integral to the low speed shaft assembly, and an epicyclic planetary gearbox, which is notable for its compact size and maintainability features. The alloy steel quill shaft is configured with a torsional stiffness designed to dampen rotor torque fluctuations. The drive train arrangement is shown in Figure 4.

The wind turbine tower is a soft, monocoque shell structure. This configuration was selected because of its lower weight and cost factors, minimum wind blockage, and its capability to withstand the two-per-revolution bending loads induced by the rotor motion.

The electronic control system provides all functions necessary for fully automatic, unattended operation as well as continuous system monitoring and start-up/shutdown control from a remote terminal. Control and monitoring functions are performed by a single microprocessor controller located within the nacelle. Rotor tip pitch angles are controlled by the microprocessor through a closed loop electro-hydraulic servo system capable of driving the blade tips at a variable rate of up to 15 degrees/second. During operation the microprocessor integrates sensed power, RPM and collective pitch angle for pitch control processing and maintains 1) a nominal blade pitch angle during below-rated operation or 2) a constant power output level when operating at or above rated wind speeds. The microprocessor also monitors wind sensor outputs for start-up determination and to determine yaw error and initiate yaw correction.

## SITE ACTIVATION AND TESTS

In October, 1979, the DOE/NASA selected the Bonneville Power Administration (BPA) to be operator of the first three machines. The BPA had proposed a site near Goldendale, Washington. The site selection enabled the detailed site activation planning to be completed and the initiation of site surveys. One of the first factors considered was the arrangement and positioning of the three units considering the terrain and the prevailing winds. Once the location of each of the machines was defined, borings were made to verify the suitability of the baseline tower foundation designed from the soil criteria of the contract statement of work. The data from these borings resulted in revision of the tower foundation from a spread foundation to use of foundation rock anchors.

In early 1980, BOECON, the construction subsidiary of Boeing Engineering and Construction, moved an office to Goldendale and began preparatory work to set up the construction site. Actual site activities started in March, 1980 and included excavations, forms, embedments, and pouring of concrete for all foundations.

Completion of the tower foundation was accomplished with a pour of 400 cubic yards of concrete in an octagonal underground pad. The 72 installed anchor bolts extend 8.8 meters (29 feet) below the base of the concrete foundation into solid rock. The four tower base sections were bolted to the buried foundation and welded together along field splices. The remainder of the tower was then erected by vertically stacking each of the tower sections and welding it to the lower tower section along field splices.

Site electrical installations installed at ground level for each machine included switchgear, transformer, and a grounding grid. Electrical power panels were installed inside the tower bases and power and signal wiring were connected from the tower base and up the raceway to the yaw slip rings at the top of the tower in preparation for installation of the nacelle on top of the tower. Site nacelle assembly operations included installing the gearbox, generator, lube module, and roof-mounted equipment. Each nacelle was then subjected to an integration test at ground level to verify proper operation of all significant functions before committing it to installation at the 61 meter (200 foot) elevation. The assembly and erection flow and the transition to the testing sequence are shown in Figure 5.

Integration testing of each nacelle included 1) continuity testing of all of the electrical wiring, 2) control system tests to subject the nacelle control unit (NCU) and associated sensors to operational and failure mode scenarios, and 3) operational tests of the gearbox, lubrication system, pitch system, and the yaw system. After completion of the nacelle integration test, each nacelle was installed on its respective tower using a gin pole.

The gin pole used for the MOD-2 cluster is a 73 meter (240 foot) truss boom with 90,000 kg (100 ton) capacity, secured and manipulated by steel cables. The gin pole itself was first load tested prior to



lifting the nacelle. Recertification of the gin pole by load testing was accomplished after reassembly at each of the other two wind turbine sites. Use of the gin pole at the MOD-2 cluster has been a cost-effective way of accomplishing the installation requirements of the site (versus the higher cost of renting a ringer crane for the extended period required).

After assembly, each rotor was also integration tested prior to installation on the nacelle. Tests conducted include electrical wiring continuity, operation and setting of the pitch system blade position potentiometers, tests of the ice detector and part of the crack detector system, operation of the pitch system actuators and hydraulic system, and verification of all of the engineering instrumentation system sensors and wiring. After successful completion of the rotor integration test, each rotor was installed on its nacelle using the gin pole. Figure 6 shows a rotor lift, and Figure 7 shows the completed wind turbine.

Pre-rotation activities included drive train alignments (possible only after the weight of the rotor is installed on the nacelle) and rotor strain gage calibrations. Integration testing of the completed machine was then accomplished. This test series included some of the same tests run on the ground, but with a complete system and all of the operational sensors installed. End-to-end testing of the engineering instrumentation system from the transducers through to the NASA Mobile Data System (MDS) was also accomplished. A final pre-rotation confidence test was then run prior to committing the machine to wind-powered tests.

Wind-powered tests are comprised of checkout and acceptance tests. On WTS 1, a series of qualification tests was also run to satisfy those system qualification test requirements which could only be accomplished during wind-powered tests. After wind-powered operation was verified during the checkout test, acceptance tests were run to demonstrate that the machine is fully operable and ready for acceptance. Included in these tests were wind-powered operation for 100 hours, operation through various operating regimes, specified numbers of start/stop cycles, demonstration of fail safe system operations, and operability demonstrations of all WTS systems.

As of June 1, 1981, all three machines had completed system checkout, WTS 1 and WTS 2 had completed acceptance test requirements, and WTS 3 had completed 50% of acceptance test requirements.

## **CURRENT SITE STATUS**

Figure 8 shows how the MOD-2 cluster is configured. The spacings between the three wind turbines are approximately 5, 7 and 10-rotor diameters. These spacings enable evaluation of wake effect of one of the turbines on a downwind turbine. The prevailing wind at Goodnoe Hills is from the west, and relatively common wind conditions result in test conditions enabling data on wake effects over 7 and 10-rotor diameters. Some-

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what fewer but adequate opportunities are available for testing at 5-rotor diameters. The location of the two met towers was optimized to assure that at least one, and usually both, of the met towers receive unperturbed wind during required test conditions.

Multiple operation of all three machines was first accomplished in May, 1981, initiating MOD-2 cluster operation. Both of the met towers and the BPA substation had been installed and checked out earlier and were operational. Construction equipment had been removed and the gin pole disassembled and stored on site.

The nature of the testing of the MOD-2 cluster, including aerodynamic wake effects of multiple wind turbines, requires simultaneous recording of instrumentation on all three machines as well as met tower data. The MOD-2 intersite data system was designed, installed and checked out to accomplish this objective. The data collection center for this system is housed in a 3 by 4.5 meter (10 by 15 foot) building adjacent to WTS 2. Operation of the data center was initiated in April, 1981, and the capability is provided to record and display data from the three wind turbines and the two met towers. In addition to recording analog tapes for data analysis, the data center also houses two computers for formatting data to be sent to BPA and the Battelle Northwest Laboratory. Strip chart recorders, a line printer, and a CRT present real time data displays to enable test control. A patch panel is included to permit data access to organizations requesting test data. To facilitate post-test processing, all of the data is recorded on a single tape recorder with a common time base.

Engineering data is collected on each wind turbine using the Engineering Instrumentation System (EIS) designed and installed as part of the NASA data system used on all NASA large wind turbines. This system employs one rotating FM multiplexer mounted on the low speed shaft and one FM multiplexer mounted on the nacelle wall to multiplex a total of 64 channels at any one time. A total of 80 transducers are available on each machine and up to 40 may be selected for cluster tests. During qualification, checkout testing, and acceptance testing of the individual wind turbines, the NASA-provided Mobile Data System (MDS) was used for data recording and display. Having substantially completed these activities, the MDS has been released for other NASA programs.

Met data are also transmitted from the two met towers to the data center. Transmission of all of the data to the data center is accomplished using fiber optics to preclude the possibility of electrical interference from the adjacent buried power output cables which are located a few inches from the FM (analog) data cables (see Figure 8 for approximate cable routing).

## PRELIMINARY TEST RESULTS

Table 2 summarizes operation of the three wind turbines to date. During the majority of the checkout and acceptance testing period of each wind turbine, the MDS as well as most of test team, was required for testing. One hundred hours of operating time are required for completion of the test requirements for each machine. As of June 1, 1981, the hundred-hour requirements had been met for WTS 1 and 2, and test emphasis was shifted to WTS 3.

Substantial early wind power testing was accomplished on WTS 1 prior to attempting to synchronize with the utility. A lesser period of presynchronization test time was accomplished on WTS 2. Satisfaction of the presync test requirements during testing on WTS 1 and WTS 2 has resulted in relatively short periods of nonsync operation on WTS 3.

During normal automatic operations, synchronization with the utility is usually accomplished in less than two minutes after reaching rated speed. Power generated has averaged between 1000 kw and 2000 kw during testing, although all three machines have operated over the power spectrum from 100 kw to above rated (2500 kw). In late May, 1981, all three machines were simultaneously operated on-line with no problems.

Test data obtained on all three machines have been used to verify the MOD-2 design, satisfy checkout and most of the acceptance test requirements for the cluster, and make suitable adjustments to subsystems to optimize the operation of each machine. Noteworthy are the control system improvements that have resulted in significantly improving power quality (assuring that power output is relatively insensitive to wind gusts) and significantly reducing tower and rotor loads by use of a notch filter and optimizing the gain setting.

Preliminary test data on power output versus wind speed is shown in Figure 9. The data points are relatively well grouped showing consistent data over several days of operation. The data is shifted to the right compared to the design curve, but optimization of power output versus wind speed (controlled blade position versus wind speed) has not yet been accomplished. Detailed analysis must yet be accomplished to verify the preliminary data.

## FUTURE PLANS/ACTIVITY

Continuing activities at the Goldendale site will include completion of acceptance test requirements on WTS 3 and formal NASA acceptance of all three wind turbines. These actions will be accomplished in concert with BPA assumption of normal operation and maintenance functions, and commencement of a two-year test and evaluation program. This two-year program will be conducted as a joint government/industry team effort with specific activities planned and controlled by a working group chaired by NASA LeRC and comprised of BPA, NASA, BEC and Battelle representatives. The scope of effort under this program

will encompass special tests (noise, TV interference, aerodynamic wake effects, utility interface); hardware product improvements; performance optimization and improvements; system availability and maintainability evaluation; implementation of performance, maintenance, and reliability data collection systems; refinements/improvements to operating and maintenance procedures; and development of a cost-effective supply support program.

The ultimate goal is to achieve maximum commercial viability of the MOD-2 wind turbine through knowledge and experience gained from the Goldendale installation.

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**TABLE 1. PROGRAM MILESTONES**

● Go-ahead _____	August 1977
● Conceptual design complete _____	July 1978
● Preliminary design complete _____	November 1978
● Detail design complete _____	May 1979
● Fabrication start _____	June 1979
● Site selection for first three units _____	October 1979
● First unit	
● Start site preparation _____	March 1980
● Site performance complete _____	June 1980
● Component fabrication complete _____	July 1980
● Tower installation complete _____	August 1980
● Nacelle integration and tests complete _____	August 1980
● Installation complete _____	October 1980
● Initial rotation _____	November 1980
● Synchronized power production _____	December 1980
● Second unit	
● Installation complete _____	March 1981
● Third unit	
● Installation complete _____	May 1981
● Fourth unit	
● Medicine Bow site selected _____	April 1981
● Installation complete _____	December 1981

**TABLE 2. MOD-2 OPERATIONS SUMMARY**

	Operating time (hours)	Time On-Line (hours)	Power Generated (KWH)
WTS No.1	107	84	99,400
WTS No.2	122	112	138,000
WTS No.3	19	18	24,000
Total	248	214	261,400

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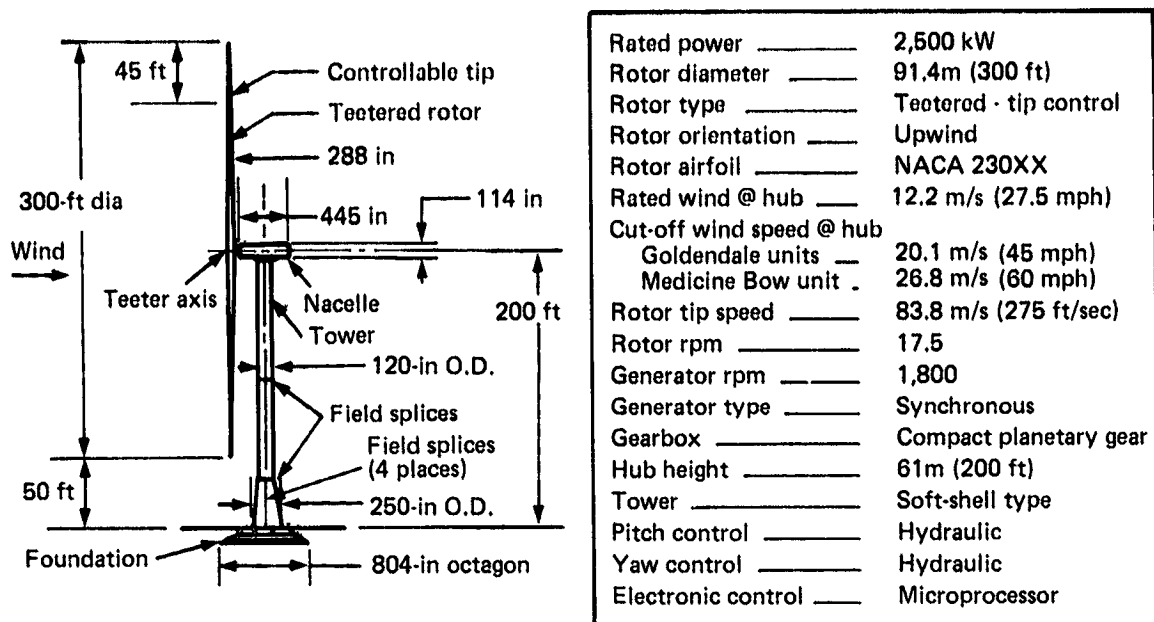


FIGURE 1. MOD-2 CONFIGURATION FEATURES AND CHARACTERISTICS

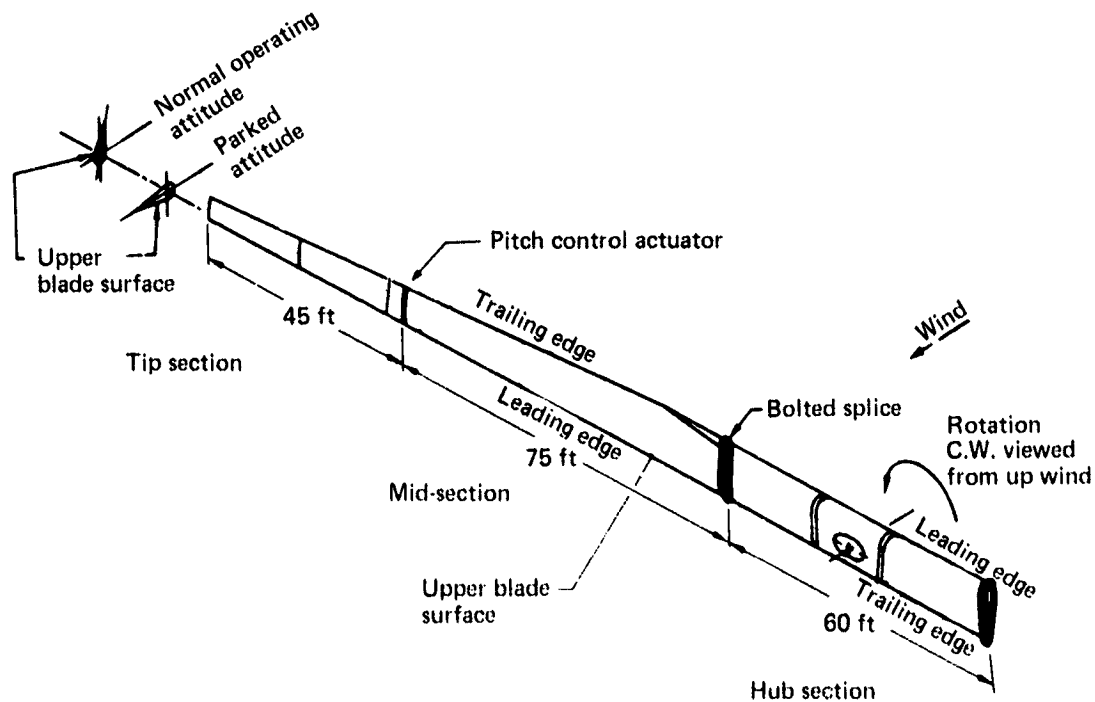


FIGURE 2. ROTOR BLADE CONFIGURATION

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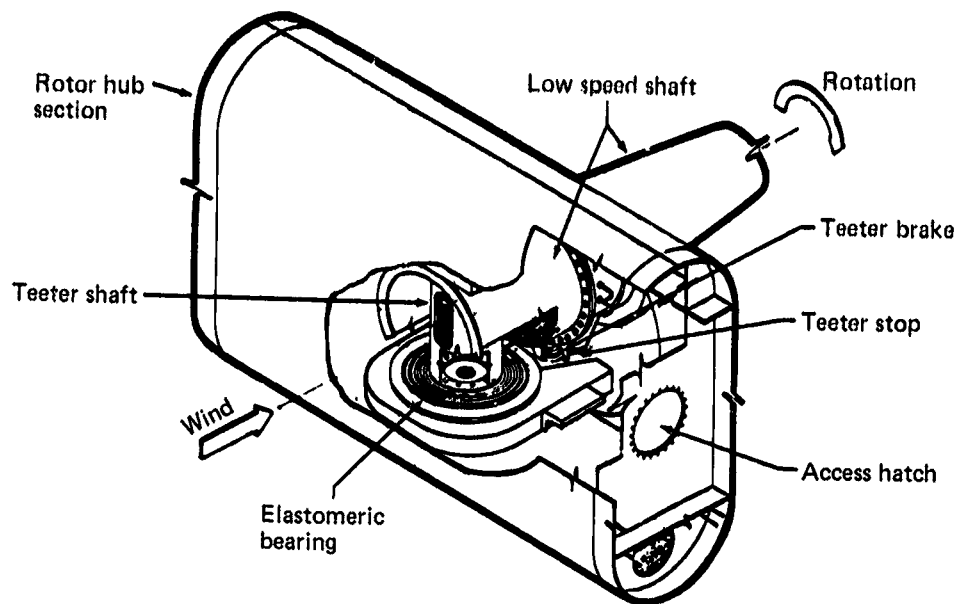


FIGURE 3. ROTOR HUB CONFIGURATION

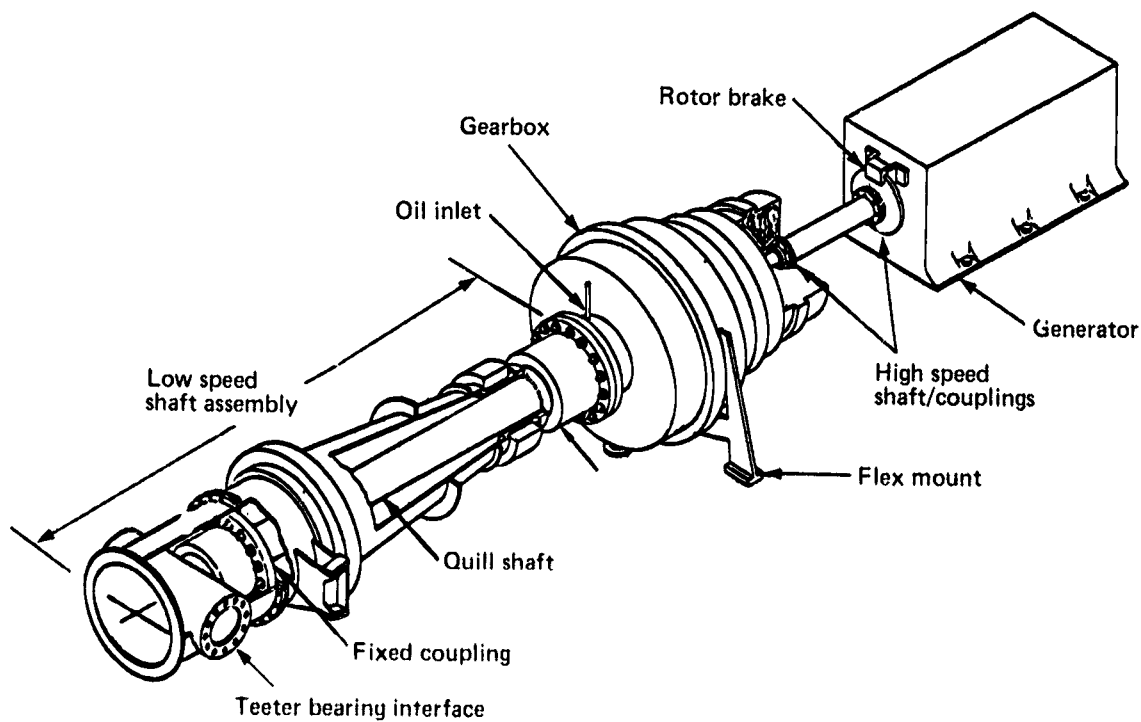


FIGURE 4. DRIVE TRAIN ARRANGEMENT

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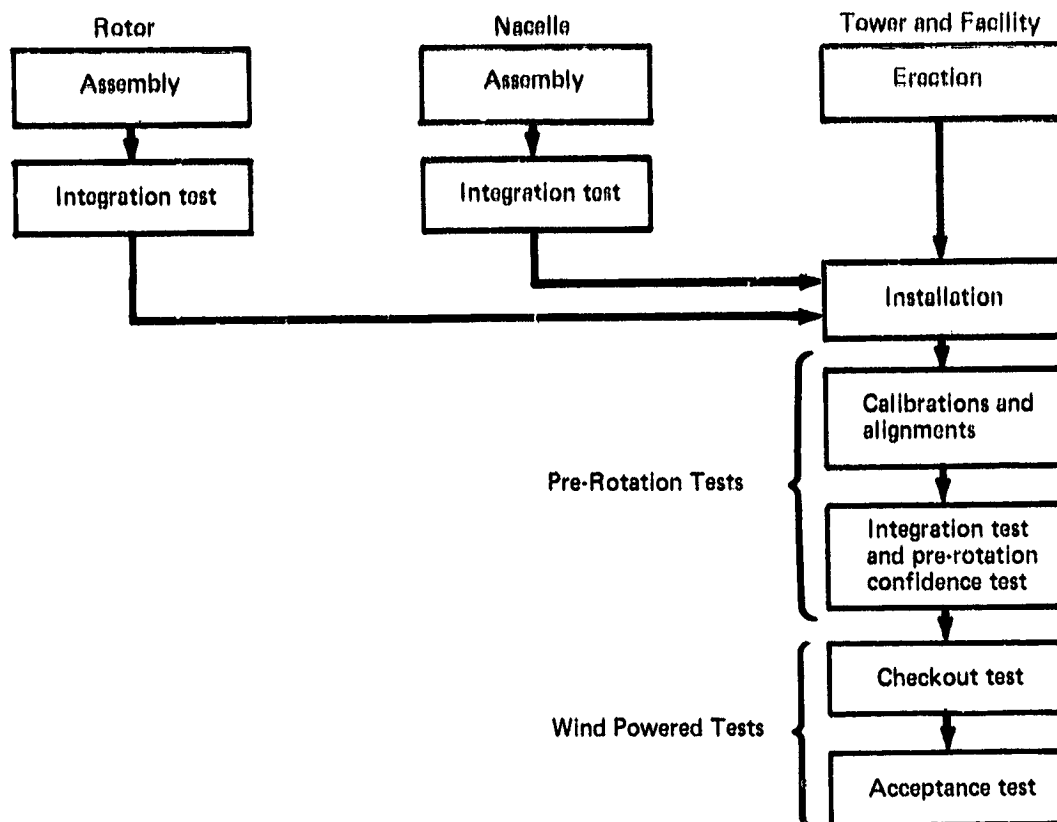


FIGURE 5. MOD-2 WTS SYSTEM TEST FLOW



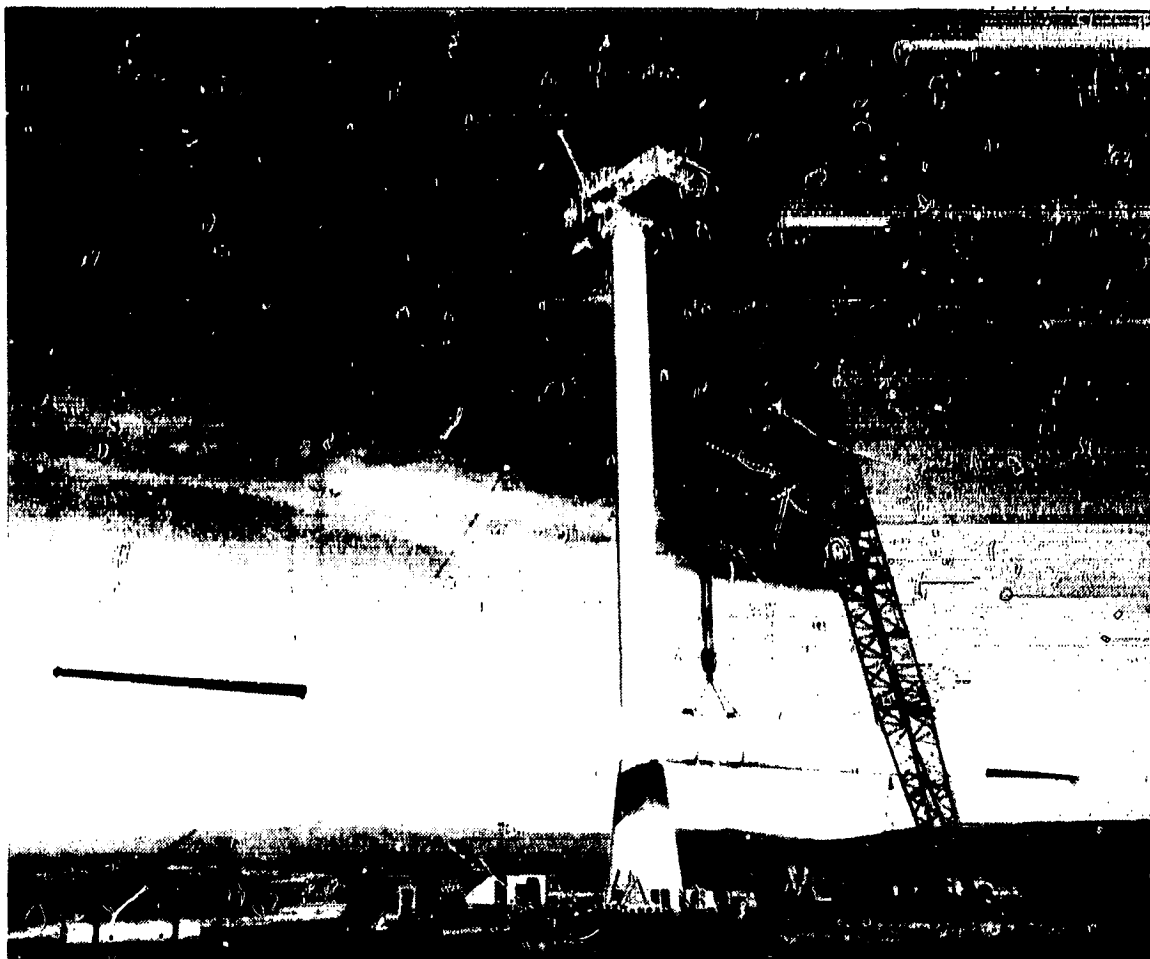


FIGURE 6. MOD-2 INSTALLATION

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FIGURE 7. MOD-2 WIND TURBINE

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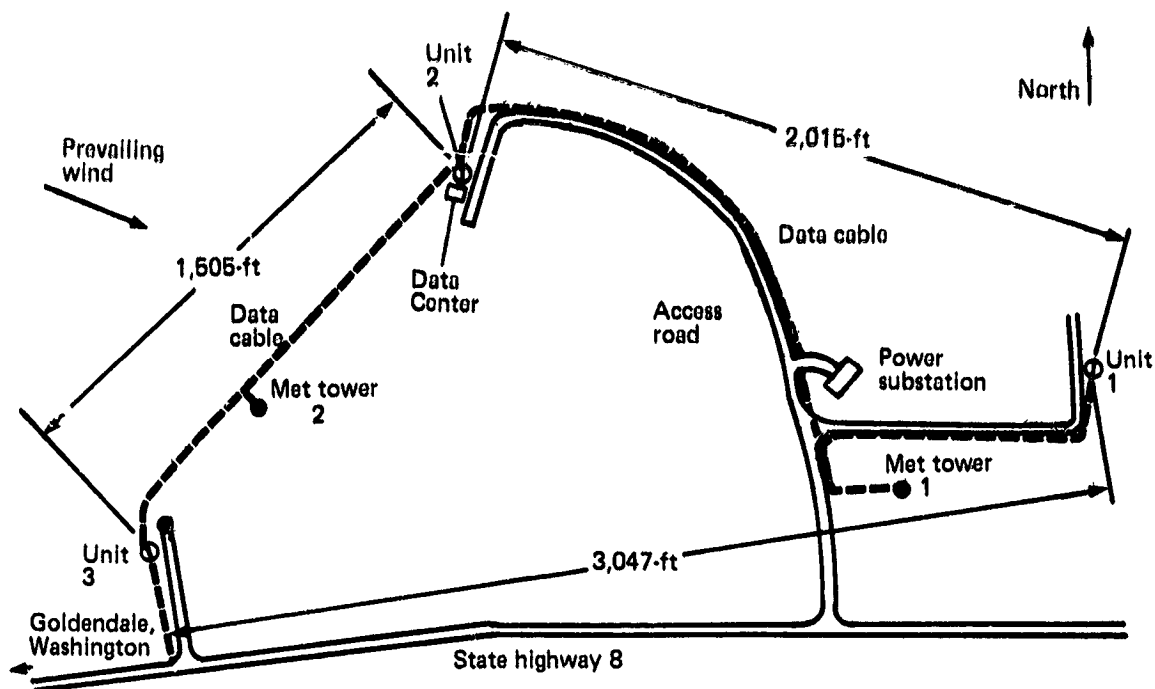


FIGURE 8. SITE PLAN (INCLUDING DATA ACQUISITION SYSTEM)

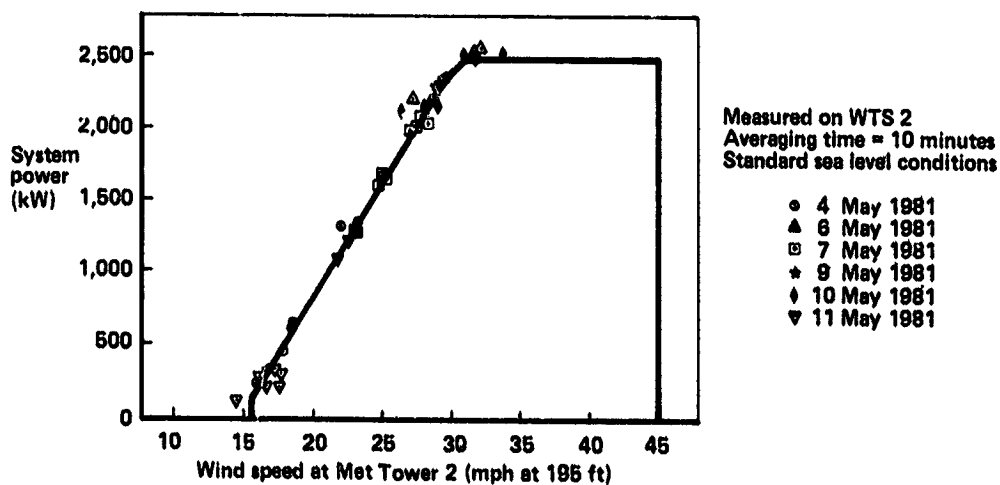


FIGURE 9. VARIATION OF MOD-2 POWER OUTPUT WITH WIND SPEED

## QUESTIONS AND ANSWERS

R. A. Axell

From: A. S. Jagtiani

- Q: 1) What is the distance in foot between units 1, 2 and 3?  
2) Is the support steel corton steel, galvanized steel or is it painted from the outside?

- A: 1) Distances between units:  
    #1 to #2 - 7 rotor diameters or 2100 feet  
    #2 to #3 - 5 rotor diameters or 1500 feet  
    #1 to #3 - 10 rotor diameters or 3000 feet  
2) The tower is A572 grade 50 Ksi steel and is painted in place after installation.

From: M. F. Dowell

- Q: Have much larger blade diameters of 500 ft to 800 ft diameters ever been considered for large amounts of power output?

A: Yes. This will be discussed in the Mod-5 presentation in Session VI.

From: A. Smith, Jr.

- Q: What is a tower notch filter that reduces tower oscillations?

A: It is a software filter which eliminates (notches out) responses of the pitch control system to the tower natural frequencies.

From: T. E. Susinskas

- Q: How were the tower "g" loads reduced?

A: A software "notch" filter was put into the control system to eliminate the pitch system response at the tower's natural frequency(s).

From: M. D. Zuteck

- Q: What was the cause (wind gradient, blade droop energy, etc.) of the torque oscillations which were actively damped out? What was the frequency (i.e. 2P, 3P, etc.)?

A: The power (torque) oscillations were at the natural frequency of the drive train. The frequency was approximately 0.14 Hz (0.48P).

From: B. Barron

- Q: Were the welds on the towers annealed?

A: No. There is no requirement for heat treatment as it has low fatigue loads. It is designed by high winds.

R. A. Axell (continued)

From: J. Medaglia

Q: Have you verified that all fatigue loads are now within design allowable or is tower fatigue still a potential problem?

A: *No. We are still in the process of evaluating fatigue loads on certain elements of the machine (parts of the rotor). The tower is no longer a fatigue concern.*

From: Anonymous

Q: Why was the generator trip-out not interlocked with blade tip control?

A: *Our baseline system design of the failsafe system was based on several failure modes which included generator trips and loss of computer control. Therefore, we could not rely on relating tip position with generator trip-out. Our proposed changes include keeping the generator on-line until a prescribed power level is reached. (Note: the normal shutdown of the machine does not trip the generator until 100 Kw output is reached.)*

From: D. Lingelbach

Q: Is the emergency stop button hardwired to the tip control valves or is it tied through a microprocessor?

A: *It is hardwired.*

From: Anonymous

Q: What percentage of design loads did the rotor experience during the failure incident?

A: *We went over design loads on the rotor attach bolts and plan to replace them. The rotor structure is designed by fatigue life, and so saw less than design loads. (The bolts are prestressed and therefore not designed by fatigue loads.)*

MOD-2 WIND TURBINE  
PROJECT ASSESSMENT AND CLUSTER TEST PLANS

By

Larry H. Gordon  
NASA Lewis Research Center  
Cleveland, Ohio

ABSTRACT

An assessment of the Mod-2 Wind Turbine project is presented based on initial goals and present results. Specifically, the Mod-2 background, project flow, and a chronology of events/results leading to Mod-2 acceptance is presented. After checkout/acceptance of the three operating turbines, NASA/LeRC will continue management of a two year test program performed at the DOE Goodnoe Hills test site. This test program is expected to yield data necessary for the continued development and optimization of wind energy systems. These test activities, the implementation of, and the results to date are also presented.

INTRODUCTION

Within the Federal Wind Energy Program, the U.S. Department of Energy (DOE) Office of Solar Power Applications has overall responsibility for conceiving and directing the development of technology for wind energy systems. The DOE has delegated project management responsibility to the National Aeronautics and Space Administration (NASA), Lewis Research Center (LeRC), in Cleveland, Ohio, for conducting successful design, fabrication, and field testing of large (100 kW and larger) horizontal-axis wind turbine systems for utility applications. The specific objective of the Federal Wind Energy Program and the projects by which it is implemented is the development of the technology necessary for commercially-feasible wind-powered generation of electricity.

The Mod-2 wind turbine project is the first in the Federal Wind Energy Program to be dedicated to the design, installation and demonstration of a wind turbine system of commercial scale, at a rated power of 2.5 MW. In addition, the installation of three such

machines clustered at a single site at Goldendale, Washington, is expected to test, evaluate and demonstrate the interactive and machine/grid effects of multiple, identical, machines integrated into a utility network.

The DOE selected the Bonneville Power Administration (BPA) as the participating utility of the Mod-2 wind turbine project. This utility was selected for the reasons of its scope as a large regional power-distributing organization in the Pacific Northwest and its capability of supplying valuable support in attainment of the DOE/NASA project goals.

Specifically, this paper presents the Mod-2 requirements, project flow, and a chronology of events/results leading to Mod-2 acceptance. After checkout/acceptance of the three operating turbines, NASA/LeRC will continue management of a two year test program performed at the DOE Goodnoe Hills Test site. This test program is expected to yield data necessary for the continued development and optimization of wind energy systems. These test activities, the implementation of, and the results to date are also presented.

## REQUIREMENTS

DOE/NASA awarded the contract to design and build a second generation, Mod-2, wind turbine in August 1977. The specific objective of the Mod-2 project is to establish the design and performance of a nominal megawatt-size wind turbine that can achieve a cost-of-energy for the 100th unit in production of less than 5¢/kWh including capital, and operating and maintenance costs in 1980 dollars. The wind turbines are assumed to be deployed in a twenty-five unit cluster at a site having an annual mean wind speed of 6.3 m/s (14 mph) at a height of 9.1 m.

Meeting those specifications, shown in figure 1, required use of lighter, more compact, less expensive components than those used in earlier models. The experience gained in operation of the Mod-0, Mod-0A, and Mod-1 suggested design refinements used in the Mod-2. The evolution of the technology base for the Mod-2 is shown in figure 2. From this base four major innovations evolved and formed an important part of the success of the Mod-2 design. These four major innovations were: (a) controlling the load on the blades by tip control; (b) the "soft" steel shell tower; (c) the compact, light gearbox; and (d) teetering the rotor at the hub to reduce blade loads.

The Mod-0 Experimental Wind Turbine near Sandusky, Ohio was used to simulate the soft tower, the teetered hub, tip control blades and the upwind rotor. Figure 3 shows the testing of the Mod-2 tip control configuration on the Mod-0 turbine.

## PROJECT FLOW

To meet the design requirements, the Mod-2 project was structured toward a program of comprehensive trade-off and sizing studies, use of innovative design ideas where advantageous, and design for simplicity and minimum operating and maintenance costs.

Shown in figure 4 is the overall program schedule which includes six important phases as follows:

- 1) Conceptual Design - Trade studies (particularly examining optimization of rotor size from 300 feet up), developmental tests and design criteria sensitivity studies were used to select a wind turbine configuration which best meets cost goals and technical requirements. This phase was extended four months to include additional trade-off studies, which resulted in a COE projection of less than 4¢/kWh in 1977 dollars. A conceptual design review was held June 1978 and written approval by the DOE and LeRC Wind Energy Project Office was given to proceed. An example of a typical trade-off study as well as a summary of all trade-offs are shown in figures 5 and 6, respectively.
- 2) Preliminary Design - Layout drawings were prepared and analysis and expanded testing were conducted to further define and evaluate the configuration selected in the Concept Design phase. Some long-lead procurement items were ordered. The design review was held in November 1978, and written approval to proceed was given by the DOE and the LeRC Project Office in January 1979.
- 3) Detailed Design - Final drawings and analysis and shop planning documents were prepared. Tooling design and fabrication began and long-lead materials were procured. Final developmental testing was performed. The detailed design review was held in May 1979 documenting the work to date, with updates in the analysis and planning as required. A key programmatic decision point occurred at this time when DOE approved the next phase, and specified a total of three machines to be procured. Site selection, which was also to be specified by DOE at this time, was deferred until October 1979. In October DOE selected the Goodhoe Hills site, near Goldendale, Washington, with the Bonneville Power Administration (BPA) as the participating electric utility.
- 4) Fabrication - This aspect of the project was probably the most difficult to coordinate and maintain on schedule. Figure 7 shows pictorially how the components literally came from all corners of the USA. Major assembly of the nacelle was performed by Bucyrus Erie in Pocatello, Idaho, the rotor was manufactured by Pittsburgh Des Moines Steel and the tower by Chicago Bridge and Iron in Salt Lake City, Utah. Although the primary gearbox was supplied by Stal-Laval in Sweden an alternate gearbox has been manufactured by Philadelphia Gear in Philadelphia, Pa., and is presently undergoing checkout spin testing.



5) Installation, Checkout and Acceptance - Site preparation work began at Goodnoe Hills in March 1980 following the selection of subcontractors and the conclusion of an interim agreement with the landowner to permit construction work to begin. BPA held a "ground-breaking" ceremony at the site in April 1980. Installation of meteorological towers (PNL and BPA) was completed by July 1980. All foundations were poured and cured and the first wind turbine tower erected by August 1980. Integration testing of the first nacelle was completed at Bucyrus-Erie and this nacelle was installed on its tower in September 1980. Following the successful first rotation of turbine No. 1 in November 1981, turbines No. 2 and No. 3 likewise began operating in March 1981 and May 1981, respectively. BPA held the official DOE Cluster Dedication on May 29, 1981 with all of the turbines capable of producing power to the BPA grid. Each of the three turbines is presently in the acceptance test phase.

Although originally targeted for completion by July 1981, the acceptance test schedule has been revised to reflect the recovery plan necessitated by the failure of the emergency shutdown system of turbine No. 1 on June 8, 1981. Failure analysis and corrective actions have been scheduled for completion by end of July 1981. Incorporation of the corrective actions during August 1981 will return turbine No. 2 and No. 3 to safe operating conditions in September 1981. With available winds, acceptance testing of turbines No. 2 and No. 3 is targeted for late September 1981. Turbine No. 1 damage assessment will be completed by August 1981 with replacement of the generator, quill shaft requiring long lead times. Consequently, acceptance testing on turbine No. 1 will not resume until late December 1981. This recovery activity for the Mod-2 cluster is noted in figure 4.

6) Two-Year Operational Field Test - During this phase, the Bonneville Power Administration (BPA) will provide operational and maintenance support for the wind turbines. This support is defined in an Interagency Agreement signed by LeRC and BPA in September 1980. BPA has agreed to purchase the net power generated by the three wind turbines for 2.5¢/kWh. Under a separate contract with BEC, technical support (including limited machine modifications to meet project goals and special maintenance) will be provided.

## ASSESSMENT

The design, fabrication, assembly, and synchronization of the three Mod-2 turbines certainly represents a major advancement in the development of large horizontal axis wind turbines. It is believed that these turbines, manufactured on a mass-production basis, have retained the original busbar energy cost goal (100th unit) of less than 4¢ per kWh (1977 dollars). Single units produced in today's market are currently capable of producing energy at costs of about 8¢-10¢/kWh.

Although it is premature to assess the multiple year operation of the Mod-2's, preliminary performance testing over the entire power range in winds up to 45 mph has been quite encouraging. Minor problem areas, technical and operational, have occurred as in any testing associated with prototype units. Although some of these areas remain unresolved at the present time, none is believed to be of such a magnitude to preclude future planning and operation of large scale wind turbine farms.

With regards to the continued planning necessary to make wind farms a reality, it was interesting to observe that during the initial operation of the three Mod-2's, the time period from first rotation to first synchronization became increasingly less; from 1-1/2 months to less than a week. In fact, if winds had been available for sufficient duration, the third Mod-2 would have accomplished these two milestones within the same day.

This learning curve, so important in the confidence necessary in planning wind farms, was also evident during the construction phase. Nacelle lifts and rotor lifts were performed routinely by the time the third turbine was erected. Transporting five rotor sections for on-site assembly was reduced to three sections with the complete shipping of the rotor tip/mid sections as a single (120 ft.) load.

As initially stated, a detailed assessment of all aspects of the Mod-2 program is premature. However, a visit to the Goodnoe Hills site has already convinced many that large wind turbines are a reality. The commercialization of this reality depends on providing a high level of confidence in the long term operation of large wind turbines. After the first year of operation (June 1982), a detailed assessment of turbine operation will be made. At that time DOE will assess plans for continued experimental operations and/or the disposition of the turbines. The comprehensive test plan defining the roles and responsibilities of various organizations involved in the operational field test phase forms the basis for the Mod-2 Test Project.

## TEST PROJECT

As presently scheduled, installation of the three clustered Mod-2 wind turbines at the test site, known as Goodnoe Hills near Goldendale, Washington, will be completed by the end of CY-81.

The Mod-2 wind turbines offer a unique opportunity to study the effects of single and multiple wind turbines interacting with each other, the power grid, and the environment. During the two years following acceptance of the three machines, the Mod-2s will act as a wind power laboratory, while also functioning as part of the Northwest power system through the Klickitat County Public Utility District.

During this cluster operational period, various organizations are expected to be conducting tests individually and/or jointly at the Mod-2 wind turbine site. The objective of this test project is to ensure orderly scheduling and performance of the respective tests and to maintain wind turbine system security. A Test Project Review Board (TPRB) and a Test Facility Operations contractor has been established by the Lead Test Center. However, implementation of the various test project areas will be the prime responsibility of the Lead Test Project organization. These Lead Test Project organizations are expected to include the LeRC, BPA, BEC, SERI, Battelle Pacific Northwest Laboratories (PNL) and others.

### TEST PROJECT PLAN

The fundamental strategy of the test project plan is both aggressive and flexible. In accordance with current priorities of the DOE Office of Solar Power Applications, primary emphasis will be placed on the field test operation of the wind turbine cluster. Secondarily, the cluster can also be utilized as an experimental testbed for supporting related wind energy system development of a moderate degree. The flexibility of the plan's strategy is conducive to management and attainment of full development of the Mod-2 wind turbine cluster. Cooperation between the DOE and the NASA will be maintained through joint LeRC/BPA approval of field test operation activities entailed by the project.

The interrelationship of the test project plan, the LeRC/BPA Interagency Agreement and the controlling test plans describing test activities at the Mod-2 wind turbine cluster site is shown in figure 8.

The Interagency Agreement is the basic understanding of the working relationship between the LeRC and BPA for the purpose of implementing this project. It is entitled "Integration and Operational Field Testing of 2.5 MW Mod-2 Wind Turbines."

The test project plan defines not only the present responsibilities of the participants leading to the initial checkout and acceptance of the Mod-2 cluster (Integration), but also the cooperative management of an extended test program (Field Operation) that is expected to provide valuable data to be used in the continued development and optimization of wind energy systems (Experimental Machine Utilization).

The test plans are detailed descriptions of the work to be accomplished by the respective described activities or tasks. In respect to each activity or task described, the test plan states test objectives, conditions, facility requirements, operational impact, test matrix, documentation, resources and schedule.

## TEST SITE DESCRIPTION

To make the most of the research opportunities afforded by the Mod-2 turbines, each machine has been assigned a separate primary test function, while still working as part of the multi-unit wind farm.

As shown in figure 9 and 10, Unit 2 farthest from the road, will be kept in operation whenever possible, and will be quickly brought back on line by Boeing or BPA crews in the area when it shuts down, in order to determine the maximum energy yield which can be produced by the Mod-2 at the Goodnoe Hills site.

Unit 3, nearest the road, will run under "real world" utility conditions. When the machine shuts down and requires inspection, crews from BPA substations will be scheduled to work on it. This will give utilities an idea of the staff commitment necessary to maintain a wind turbine, and the energy production achievable under routine operating conditions.

Unit 1, nearest the visitor's center, is the machine where ideas for improving the design or operating limits on the Mod-2 will first be tested, to further develop wind turbine technology.

The spacing of the Mod-2 turbines at the test site is also considered as an important test feature. The three machines are purposely positioned at the corners of an irregular triangle whose sides are five, seven and ten blade rotor diameters (i.e: 1,500, 2100, and 3,000 feet) long. This will allow researchers to test the effects of the machines on one another at different spacings.

Two meteorological towers--a 200-foot BPA tower and a 350-foot Battelle PNL tower--collect windspeed, wind direction and other atmospheric data at the Goodnoe Hills site.

The data center is the heart of the Goodnoe Hills data acquisition system. A function block diagram of the intersite data system is shown in figure 11.

## TECHNICAL PLAN

As illustrated in figure 8, the activities provided by this test project consist of three major elements in the technology development and demonstration of the Mod-2 wind turbine. These elements are:

- 1) Integration - The tasks relating to this element are primarily concerned with the effort necessary to achieve first rotation of the three Mod-2 turbines and acceptance by LeRC for turnover to BPA. For this reason, the specific tasks have not been included in this paper.

2) Field Operation - For a period of approximately two years, this element will be devoted to verification of the baseline performance and establishing the operational characteristics of the Mod-2 wind turbine cluster.

3) Experimental Machine Utilization - This element is an important aspect of a planned long-term project within the Federal Wind Energy Program to extend operation of existing DOE/NASA wind, in the interest of maximizing data and component technologies development through real-time machine operation. Hence, this aspect of the test project will specifically be concerned with analysis and testing pertaining to areas of:

- o cluster/array analysis
- o array maintenance evaluation
- o advanced concepts verification

Since the Field Operation phase is the current active portion of the Mod-2 test project, a brief description of the various test areas to date is as follows:

Performance Test Plan - Performance evaluation of these machines in the three unit cluster configuration will commence with acceptance of each turbine. It is planned that the two year test period will evaluate baseline performance as well as performance improvements which can be achieved through modifications of hardware, software, and operating procedures. Specific performance tests planned to date include:

#### 1) Baseline System Performance Tests

The primary goal of this Baseline System Performance test is to evaluate the performance achieved (or achievable) by the baseline configuration. This will be measured in terms of power output as a function of wind speed and the energy produced as a fraction of the energy available in the actual wind environments experienced.

A secondary objective is to evaluate and correlate the calculated power output performance versus wind speed against the actual performance achieved at each wind speed.

#### 2) High Wind Cut-Out Speed Tests

The baseline Mod-2 is designed to shutdown when wind speeds at hub height exceed 45 mph. Shutdown is initiated when a specified value of blade pitch angle is exceeded. At some wind sites a significant increase in annual energy would be achieved by operating to higher wind speeds.

Operation at off-wind yaw angles in the high wind speed regimes results in higher rotor teetering motions and associated higher cyclic loads. At various combinations of wind speed and yaw angle,

the rotor teeter motion will be sufficient to cause impacting of the teeter stops.

The primary objective is to determine the maximum wind speed at which the Mod-2 may be operated, and what modifications are required to permit the Mod-2 to operate at wind speeds above 45 mph when the wind spectrum includes significant time in the above 45 mph wind speed regime.

### 3) Power Output Limit Tests

The Mod-2 generator is rated at 3125 KVA at 7000 ft. altitude. It therefore has capability for a power output of 3125 kW if operated at a power factor of unity. At lower altitude, the generator is capable of additional power output. The limiting power output of the generator is, in general, a function of internal temperature due to losses. It may be desirable to implement wind turbine power output control based on measured generator temperature.

The Mod-2 gearbox was designed and tested at a torque loading and rpm equivalent to 3750 kW. The ability to increase power output is therefore dependent on the structural capabilities of the rotor and drive shafts. Specific objectives will be to:

- (1) Evaluate capability of rotor and drive shafts to operate at higher torque.
- (2) Establish limiting values of torque.
- (3) Develop a recommended control concept to operate at the optimum power output limit.

### 4) Low Wind Startup/Shutdown Tests

The baseline configuration initiates shutdown when the power output averaged over 51.2 seconds is less than 125 kW. Considerable operating time is lost during startup during these low wind conditions. It is anticipated that many start/stops would be eliminated and that additional annual energy could be achieved by allowing some motoring at wind speeds of approximately 11 mph. Consequently, emphasis will be placed on:

- (1) Reducing number of start/stop cycles
- (2) Increasing annual net energy production

### 5) Pitch Setting Refinement Tests

Below rated power, the control system operates at two values of fixed pitch with rate damping. The values selected may not be optimum. Revised and/or additional settings may optimize power output at below rated power.

During startup the pitch settings have been programmed as a function of wind speed and rpm to provide maximum acceleration to 10 rpm. Above 10 rpm the pitch settings are controlled by hub rate error until synchronization is achieved at 17.5 rpm.

Specific objectives for these sub-test areas will be to;

- (1) Adjust the startup algorithms to assure acceleration through 10 rpm.
- (2) Evaluate algorithm changes to minimize the time to synchronization.
- (3) Adjust pitch settings at below rated power to optimize power output.

#### 6) Yaw Control Refinement Tests

The yaw control is based on time averaging of yaw values as determined by the nacelle wind sensors. Any refinement in control algorithms which will reduce the time spent at yaw angles will improve power output by the third power of the cosine of the yaw angle.

The primary objective is to increase the annual energy produced. Sublevel objectives are to:

- (1) Reduce yaw angle excursions
- (2) Reduce time spent at angles of yaw
- (3) Reduce the magnitude and frequency of cyclic loading associated with excessive yaw angles
- (4) Reduce number of shutdowns from excessive yaw angles
- (5) Establish optimum system with consideration of the duty cycle of the yaw drive system

#### System Verification and Improvement Tests

Tests will be performed relating to long term verification of system design adequacy and design improvement. Consideration will be given to:

- o evaluating system responses to actual wind environment
- o varying teeter brake release point
- o evaluating various yaw hydraulic duty cycles
- o studying emergency shutdown procedures
- o testing generator excitation control
- o evaluating system simplification

- o incorporating power control functions
- o evaluating maintenance program

During the first year of this overall project plan, this test area will be fully defined and implemented by a lead test project organization.

#### Environmental Impact Test Plan

This test area will evaluate site specific and machine specific environmental effects at the Goodnoe Hills site. Site specific effects shall include:

- o electromagnetic interference (EMI), TVI, RI, and other established service and systems utilizing radio transmission and reception.
- o audio and infrasound studies
- o ecological impacts in flora, fauna, wildlife habitat, weather, air pollution, etc.
- o visual impacts to the public
- o safety to personnel

Machine specific effects shall include:

- o air pollution in the form of saline spray, volcanic ash, mold, spores, etc.
- o ground effects in the form of freezing/thawing soil, rodents, landscaping, and grazing.

#### Power Transmission and Distribution Test Plan

The following describes the tests and analyses which shall be performed to evaluate the impact and effects of the Mod-2 cluster on the electrical grid. Primary consideration will be given to evaluating power factor and fault protection. In addition, analysis will be made of the impacts on the hydro system effect on the intertie operation and recommendations will be made for improved scheduling procedures for wind generation. Specific test activities will consist of:

- o Electrical Power and Reactive Surges on Weak Systems
- o Single and Cluster Machine Stability on Weak Systems
- o Reverse Power Surges
- o Cluster Interaction of Reactive Power Flow
- o Power Fluctuation and Impact on System



### Machine Dynamics and Structural Analysis Test Plan

During the first year of this overall project plan this test area will be fully defined and implemented by a designated lead test project organization. The main objective is to obtain appropriate deflections, stresses, and responses of the WTS that will permit correlation of analytical predictions made from using the NASTRAN, MOSTAB, NACA/AMES STABILITY, EASY, AND LSD computer codes. Another objective is to identify possible structural "hot spots" in the WTS.

Extensive data will be taken on unit 1 in both the parked and operating modes in order to establish the structural characteristics of various components and to determine system responses for comparison with analytical predictions. Any measurements identified in early testing of unit 1 that merit additional monitoring on units 2 and 3 will be included in abbreviated measurements on those units.

### Meteorological Data Test Plan

A detailed understanding of the temporal and spacial characteristics of wind patterns and other meteorological parameters is a critical requirement of the Mod-2 cluster test program. A lack of understanding of many meteorological parameters could generate gaps in understanding many of the performance characteristics of the turbines.

Since this program will produce an extensive meteorological data base for use in other research endeavors, meteorological parameters from the two meteorological towers, and turbine output parameters from the three machine, will be recorded continuously on a centralized digital data logging system. In addition, it is anticipated that several short-term, intensive field measurement programs will produce additional meteorological data from the site. All these data will be incorporated into a data base where information is readily retrievable. Specific objectives will:

- (1) Define general climatological conditions at the site, including mean and turbulent wind patterns measured temporally and spatially, vertical variation of wind characteristics, and vertical and horizontal temperature patterns.
- (2) Provide information to be used in evaluating turbine performance evaluations, including the effect that upwind turbines have on downwind turbines due to wakes.

### Wake Effects Test Plan

As the machines become operational wake studies will be undertaken. These studies will involve special, short-term, field measurement programs utilizing a variety of measurement platforms. The data will be used to test and validate existing and future numerical and

physical wake models, and to allow parametric analysis of critical characteristics to improve the models. Wake studies will include investigation of momentum deficits as a function of distance behind the machines and wake turbulence produced by the machines.

## MANAGEMENT PLAN

The Mod-2 Cluster Turbine Test Project encompasses a broad and diverse spectrum of activities and organizations which require coordinated planning, continuous evaluation of progress and full communication and interaction with DOE and with the appropriate utility, commercial and industrial sectors.

The DOE Wind Energy Systems Division has overall program responsibility for this effort. The project management functions at LeRC will be performed in the Wind Energy Project Office located in the Wind and Stationary Power Systems Division of the Energy Programs Directorate.

Key elements of the management approach are:

1) Project Management - The Lead Test Center will provide overall management including planning, integration and coordination of the involved field test organizations. It will focus on the field test activity needed to prove wind energy system feasibility and to encourage their future use.

Project objectives and plans will be formulated and will serve as the basis for an ongoing assessment of progress against plans and requirements. The planning process will include continued interaction with the field test organizations and with utility, commercial and industrial participants.

2) Project Implementation - Lead test, shown in Figure 12, organizations will be delegated prime responsibility and appropriate authority for the day-to-day management and implementation of their designated test project. The Lead Test Center will establish broad management processes, including planning, reporting and review procedures. Existing reporting practices will be used to the maximum extent. A Test Facility Operations contractor, managed by the Lead Test Center, will provide the test operations necessary to implement the test projects established by the Lead Test Organizations.

3) Test Project Review Board - As part of the management structure, a Mod-2 Test Projects Review Board (TPRB) has been formed and is composed of representatives of LeRC, BPA, LeRC Mod-2 Contractor, Battelle PNL and SERI. The TPRB is jointly chaired by LeRC and BPA. The TPRB will review detailed test plans, schedules, and procedures associated with the testing of the Mod-2 Cluster. The primary purpose of the TPRB will be to plan and manage the testing of the Mod-2 Cluster. Specific responsibilities will be to: (a) ensure

coordination of DOE Wind Energy Systems Mod-2 test program/facility; (b) review and approve test project plans submitted by the Lead Test Project Organizations; (c) ensure dissemination of all test results, analyses, and other relevant data, information and findings; (d) ensure security of the test facility, (e) ensure cost effective utilization of instrumentation, data acquisition/reduction facilities; and (f) provide status reports of periodic review meetings.

#### TEST PROJECT RESULTS TO DATE

Prior to the June 8 incident, the Lead Test Organizations had planned that noise, wake, and TV tests would be performed throughout the months of June thru September 1981. However, with the recovery plan for the Mod-2 turbines, these test plans have been revised for September/October 1981 schedule with only two turbines scheduled to be operational.

In preparation for these tests several preliminary areas were addressed pertaining to noise and TV interference. TV interference tests were performed by BPA in February 1981. BPA in these earlier tests did not locate any home with TV reception which should receive interference from the wind turbines. The primary reason is the terrain blockage which seems to prevent front lobe interference.

Noise tests performed by SERI and NASA LeRC in February 1981 and May 1981 respectively have also been quite encouraging. SERI's preliminary results show that the acoustic output of the Mod-2 is totally broadband in nature, with no strong periodic components. The rotor noise is highly incoherent, and no rotor discreties could be found above 10 Hz, on the average. The sound produced by the Mod-2 has been described as a "heavy whoosh." Field personnel have reported that the "whoosh" could be heard clearly up to about 30-45 m (100-150 feet) away from the turbine, however, as the distance from the machine is increased further, the "whoosh" is rapidly covered by wind noise. NASA/Langley results in early May 1981 likewise indicated that only broadband characteristics were evident and the low db levels measured were similar to those commonly associated with "busy" street traffic. The noise starts to attenuate at distance of approximately 3 rotor diameters and is below recording levels at 1-3 miles downwind and 0.6 mile upwind for a single turbine.

When testing is resumed at Goodnoe Hills in September 1981 (targeted), wake tests will be performed with 5 rotor diameter information being obtained. Other testing (7 dia. and 10 dia. spacing effected) must be postponed until the entire cluster becomes operational in early CY-82. At the time of the June 8 failure and the temporary stop on continued operation of turbine No. 2 and No. 3, the performance of the three turbines were as follows:

	<u>Operating Time*</u>	<u>Energy Generated</u>	<u>Sync. Time</u>
No. 1	107 hrs	99.4 Mwh	84.0 hrs
No. 2	122 hrs	138.0 Mwh	113.5 hrs
No. 3	19 hrs	23.7 Mwh	18.5 hrs

\*One of five criteria for acceptance is 100 hours of operation

#### Concluding Remarks

The Mod-2 wind turbine project described is the second generation phase of the Federal Wind Energy Program managed by the NASA for DOE. Industry, public utilities, and the government have been working parties in this program designed to produce the technology to supply wind generated electric energy. Industrial involvement in turbine development provides the necessary commercial base, while utility operation of the evolving machines in their networks assures a viable end product in this government supported program. The design, fabrication, assembly, and synchronization of the three Mod-2 turbines at Goodnoe Hills represents a major advancement in the development of large horizontal axis wind turbines. It is believed that these turbines, manufactured on a mass-production basis, have retained the original busbar energy cost goal (100th unit) of less than 4¢ per kWh (1977 dollars). Single units produced in today's market are currently capable of producing energy at costs of 8¢-10¢ per kWh.

The Mod-2 project is now in the experimental operations phase which offers a unique opportunity to study the effects of single and multiple wind turbines interacting with each other, the power grid, and the environment during the next two years. To date, initial performance of the turbines has been acceptable but also has indicated areas for optimization. Corrective actions have been taken to modify the turbines as necessitated by the June 8, 1981 failure of turbine No. 1's safety system. Test operations are expected to be resumed in early Fall on turbine No. 2 and No. 3. Full cluster operation is anticipated in early CY 82.

#### RELATED MATERIAL

1. Boeing Engineering and Construction Company, "Mod-2 Wind Turbine System Concept and Preliminary Design Report". Vol. I & II. DOE/NASA 0002-80/2, July 1979.
2. Bonneville Power Administration, "Building the World's First Wind Farm", DOE/BP-85, May 1981.
3. Lewis Research Center, "The Mod-2 Wind Turbine Development Project", NASA TM-82681, July 1981.

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- REQUIREMENTS:
  - 300 FT MINIMUM DIA.
  - HORIZONTAL AXIS
  - WIND MODEL DEFINED
  - FAILSAFE OPERATION
  - UTILITY COMPATIBLE
  - AVAILABILITY OF 0.90
- GOALS:
  - COE  $\leq$  4¢/KWH (1977 DOLLARS)  
IN PRODUCTION

Figure 1- Design Requirements/Goals

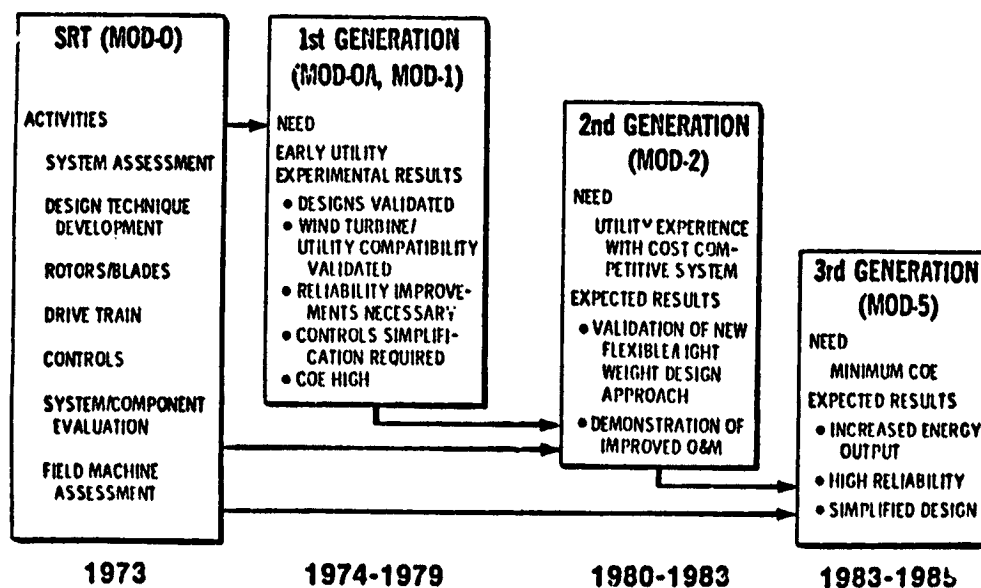
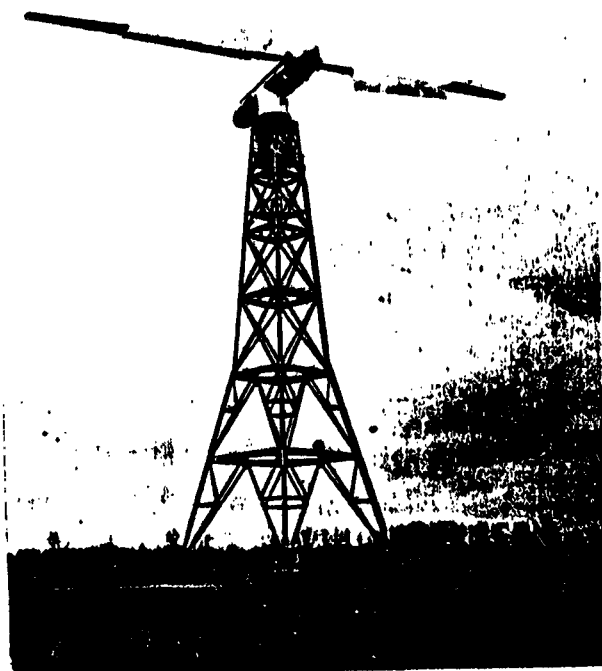


Figure 2- Evolution of Technology

MOD-0 ORIGINAL PAGE 17  
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MOD-2



- SOFT TOWER
- TIP-CONTROL BLADES
- TEETERED HUB
- UPWIND ROTOR

Figure 3-Mod-0 Technology Transfer

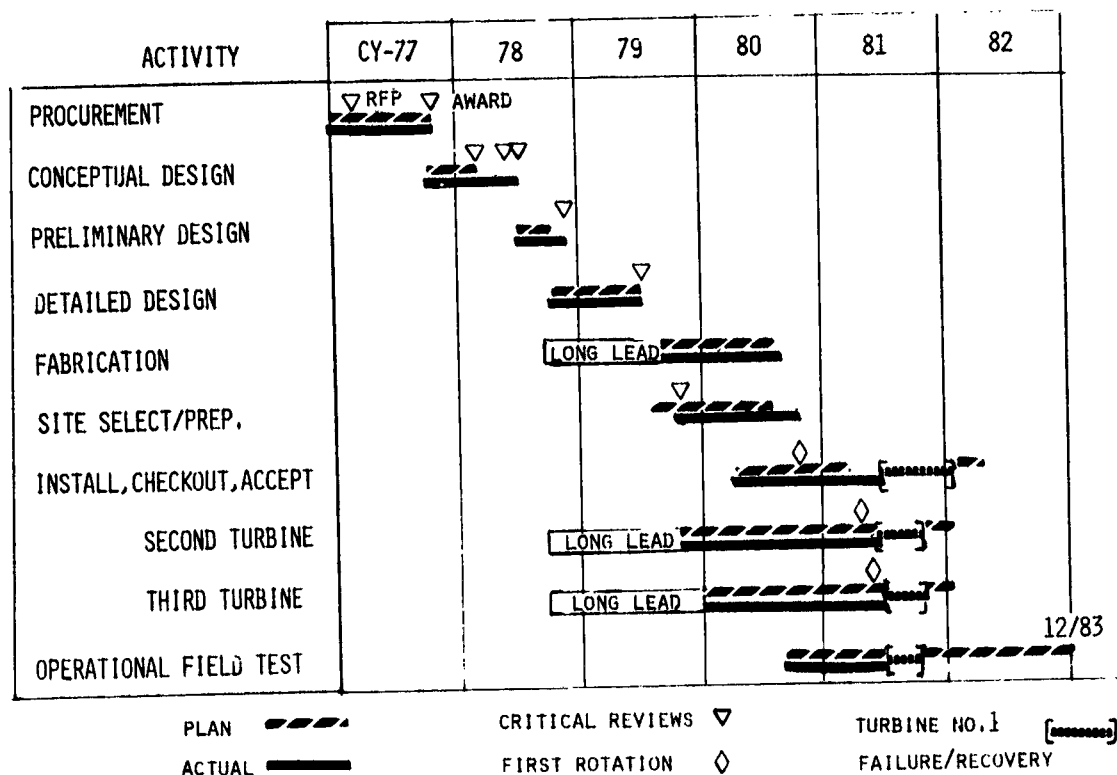


Figure 4- Mod-2 Project Schedule

**TRADE STUDY  
2 vs 3 BLADE ROTOR**

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CRITERIA	CONFIGURATION		REMARKS
	2 BLADE	3 BLADE	
ROTOR DIAMETER	300 FT	300 FT	60 FT GROUND CLEARANCE USED FOR BOTH CASES
SYSTEM $C_p$ max	.300	.396	
YAW SYSTEM COST	\$85,000	\$72,000	3 BLADE SYSTEM REQUIRES SMALLER DRIVE & BRAKES
ROTOR COST	\$260,000	\$371,000	3 BLADE HUB REQUIRES SPLICES FOR SHIPPING
DRIVE TRAIN COST	\$462,000	\$538,000	3 BLADE CONFIGURATION REQUIRES LARGER GEARBOX
SYSTEM COST-100th UNIT	BASELINE	ADDS \$166,000	
OPERATIONS & MAINTENANCE COST PER YEAR	\$20,000	\$22,000	
ENERGY OUT ( $K_{wh}$ PER YEAR)	8,686,000	8,890,000	FACTORED TO ACCOUNT FOR DOWNTIME.
COST OF ELECTRICITY	-	ADDS .28 ¢/kwh	

**CONCLUSIONS AND RECOMMENDATIONS:**

- INCREASED ENERGY OUTPUT OF 3-BLADE ROTOR MORE THAN OFF-SET BY INCREASED COSTS
- RETAIN 2-BLADE CONFIGURATION

Figure 5- Typical Trade Study

	Studied	Selected
<b>Rotor</b>	Two versus three blades Full versus partial span control Rigid versus teetered hub All steel versus honeycomb trailing edge, versus fiberglass Upwind versus downwind RPM optimization	Two blades Partial span control Teetered hub All steel construction Upwind 17.5 RPM
<b>Drive train</b>	Epicyclic versus parallel shaft gearbox Quill shaft versus fluid coupling	Epicyclic Quill shaft
<b>Nacelle</b>	Truss versus beam versus semi-monocoque Hydraulic versus electric yaw drive	Truss Hydraulic
<b>Tower</b>	Soft tubular versus stiff truss Braced versus conical base Soft versus soft-soft Tip to ground clearance	Soft tubular Conical base Soft 60 ft
<b>Electrical power system</b>	Direct versus gearbox driven generator Induction versus synchronous generator 1,200 versus 1,800 RPM	Gearbox Synchronous 1,800 RPM
<b>Control system</b>	Analog versus microprocessor (Digital) Ground versus nacelle location	Microprocessor Nacelle

Figure 6- Trade Study Summary

[illegible]

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graph TD
    DOE[DOE / NASA  
LARGE HORIZONTAL AXIS WIND TURBINE PROGRAM] -- "LERC  
LEAD MANAGEMENT" --> MOD2_WP[MOD-2 WIND TURBINE CLUSTER TEST PROGRAM  
TEST PROJECT PLAN]
    IA[INTERAGENCY AGREEMENT  
NASA/LERC AND DOE/BPA] -- "LERC" --> MOD2_IFT[MOD-2 INTEGRATION AND OPERATIONAL FIELD TESTING  
IMPLEMENTATION PLAN]
    IA -- "BPA  
REVENUE OPERATION  
ROUTINE MAINTENANCE" --> MOD2_WP
    MOD2_WP -- "SERI, BPA  
IMPLEMENTATION" --> MOD2_TP[MOD-2 TEST PLAN  
OBJECTIVE  
TEST CONDITIONS  
FACILITY REQUIREMENTS  
OPERATIONAL IMPACT  
TEST MATRIX  
DOCUMENTATION  
RESOURCES  
SCHEDULE]
    MOD2_IFT -- "LERC, SEC, PML" --> MOD2_TP
```

The flowchart illustrates the organizational structure and information flow for the MOD-2 Wind Turbine Program. At the top, DOE / NASA oversees the LARGE HORIZONTAL AXIS WIND TURBINE PROGRAM. An INTERAGENCY AGREEMENT between NASA/LERC and DOE/BPA is foundational. This agreement leads to two main paths: one for LERC (LEAD MANAGEMENT) to the MOD-2 WIND TURBINE CLUSTER TEST PROGRAM (TEST PROJECT PLAN), and another for BPA (REVENUE OPERATION, ROUTINE MAINTENANCE) to the same program. The MOD-2 WIND TURBINE CLUSTER TEST PROGRAM also leads to the MOD-2 TEST PLAN (OBJECTIVE, TEST CONDITIONS, FACILITY REQUIREMENTS, OPERATIONAL IMPACT, TEST MATRIX, DOCUMENTATION, RESOURCES, SCHEDULE) via SERI and BPA. Additionally, the MOD-2 TEST PLAN leads to the MOD-2 INTEGRATION AND OPERATIONAL FIELD TESTING IMPLEMENTATION PLAN via LERC, SEC, and PML. The MOD-2 INTEGRATION AND OPERATIONAL FIELD TESTING IMPLEMENTATION PLAN also leads back to the MOD-2 WIND TURBINE CLUSTER TEST PROGRAM via LERC and BPA.

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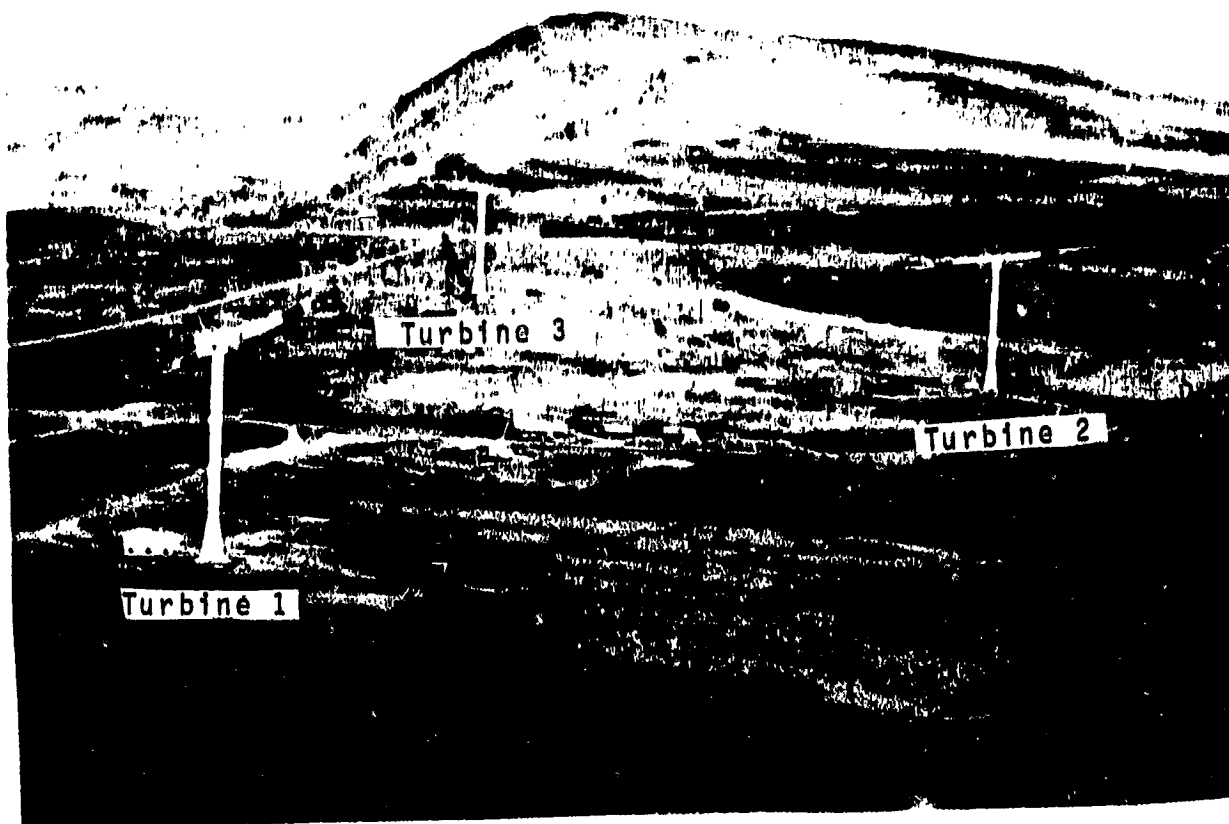


Figure 9- Mod-2 Goodnoe Hills Cluster

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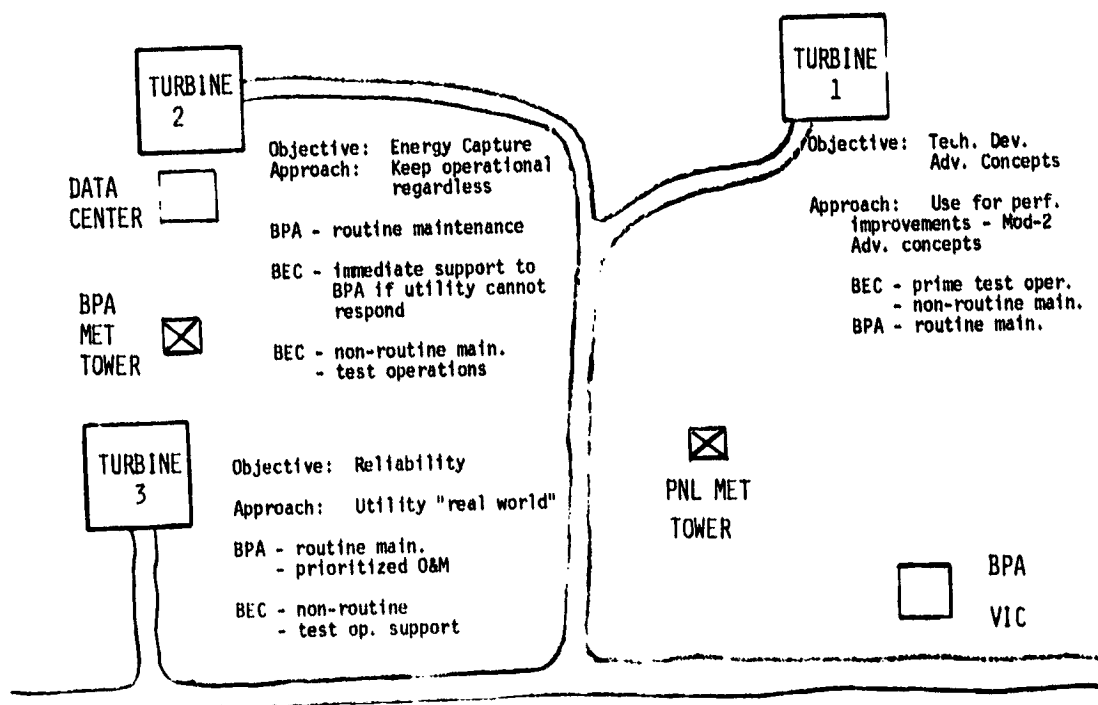


Figure 10- Mod-2 Turbine Operation Objectives

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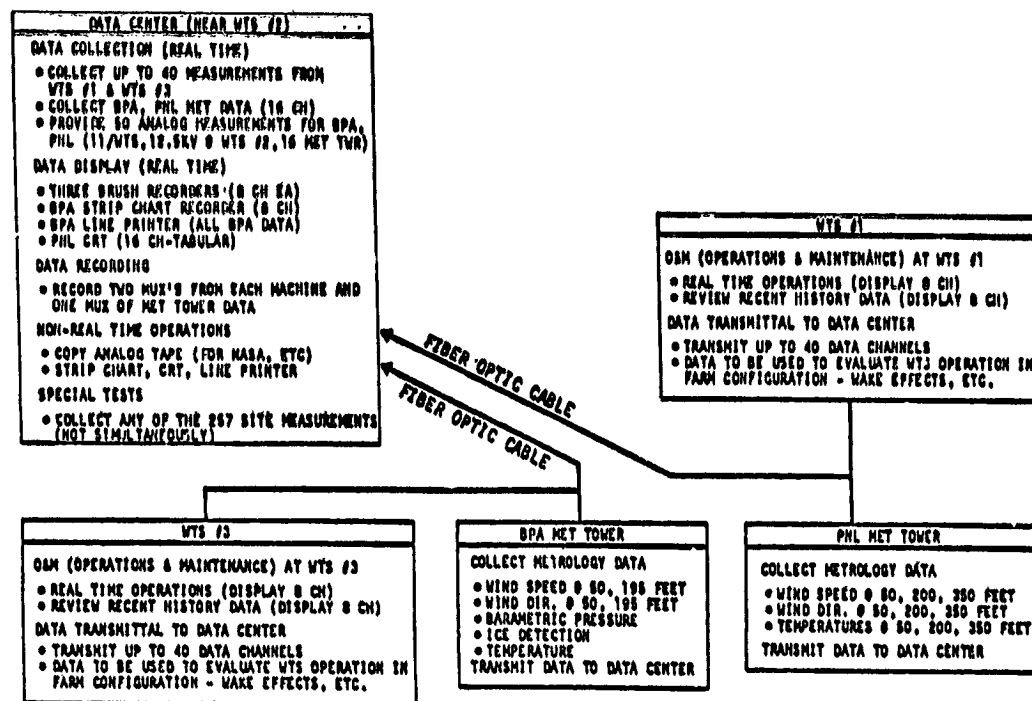


Figure 11- Intersite Data System Functional Block Diagram

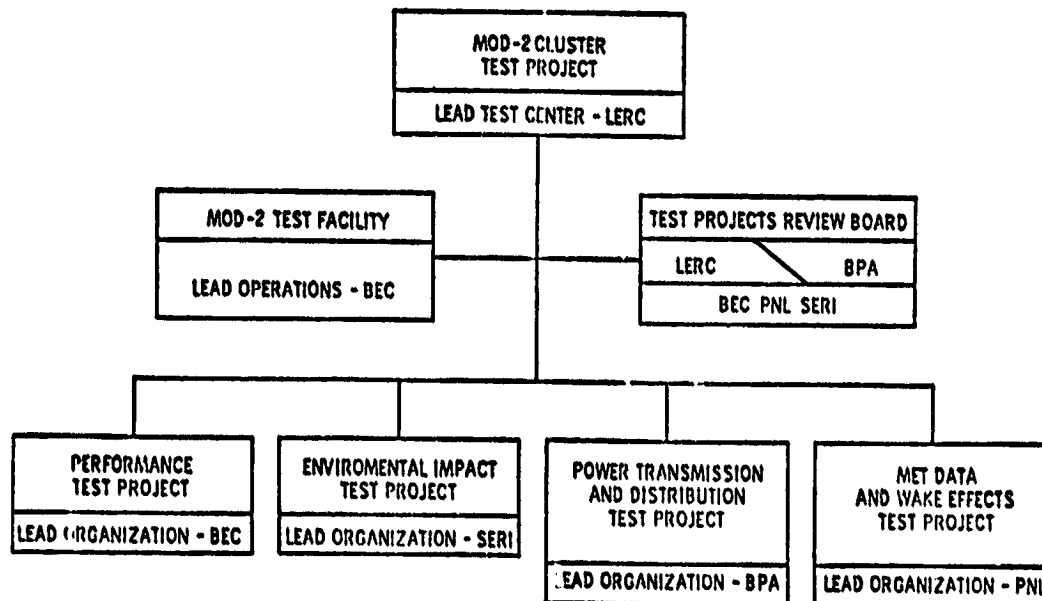


Figure 12- Mod-2 Test Project Management Structure

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## STATUS OF THE 4 MW WTS-4 WIND TURBINE

R. J. Bussolari  
Wind Energy Systems  
Hamilton Standard Division of United Technologies  
Windsor Locks, Connecticut 06096

### ABSTRACT

The WTS-4 is a four-megawatt, horizontal-axis wind turbine presently being fabricated for the U.S. Department of Interior, Bureau of Reclamation, by United Technologies' Hamilton Standard division. This unit, called the System Verification Unit (SVU) will be installed at Medicine Bow, Wyoming, early next spring. The specifications, characteristics and features of the WTS-4 are discussed. The major components-such as rotor, nacelle and tower-are described and their status in the fabrication phase is presented.

### INTRODUCTION

The Hamilton Standard WTS-4 is a 4 MW, downwind horizontal-axis wind turbine being fabricated for the U.S. Department of Interior, Bureau of Reclamation, for installation at Medicine Bow, Wyoming. This machine, called a System Verification Unit (SVU), is a potential forerunner of a number of wind turbines to be installed in Medicine Bow by the Bureau of Reclamation as part of a long-range plan to integrate wind power with hydroelectric power.

The WTS-4 SVU will be the first 4 MW wind turbine erected anywhere in the world. It reflects the culmination of Hamilton Standard's wind turbine activity under way since the early 1970s. This effort consisted largely of company-sponsored technology development until 1977 when Hamilton Standard joined in association with a large Swedish company to develop a megawatt-scale wind turbine system. After an intense competition involving five European consortium competitors, the team of Hamilton Standard and Karlskronavarvet was awarded a contract to develop the WTS-3, a two-bladed, downwind, horizontal-axis wind turbine rated at 3 MW. This unit is scheduled for installation in the fall of 1981, in the town of Maglarp in south Sweden. It will be grid-connected and operated by Sydkraft, the large, privately-owned utility based in Malmö, Sweden. Hamilton Standard's contribution to this program was the overall system design, the mechanical design of the rotor and pitch change system, and fabrication of the blades. A new factory for the manufacture of large filament-wound blades was dedicated, by Hamilton Standard, in the fall of 1980 and is now in full operation. The two blades for the WTS-3 are essentially complete and will be shipped next month to Sweden.

## SVU PROJECT

The SVU project was launched by the Bureau of Reclamation to evaluate the technical and economic feasibility of integrating wind turbines and hydroelectric facilities.

Preliminary studies by the Department of Interior, Bureau of Reclamation, indicate that current state-of-the-art wind turbines may be cost-effective when coupled with existing hydroelectric installations. They have identified the Medicine Bow, Wyoming, area as having the most promising wind resources that could be coupled with the existing hydroelectric system in the Colorado River Storage Project. Their plan is to install SVUs at Medicine Bow to evaluate the technical and economic feasibility, as well as the environmental and social acceptability of this integration concept.

The nature of economic feasibility is the expected cost of electricity for a multi-unit installation of SVU-type machines capable of generating 400,000,000 kW hours per year.

The scope of the SVU project, then, is to install and operate megawatt-scale units at Medicine Bow, Wyoming, and to train DOI personnel to manage wind turbines and future acquisitions. For this purpose, a contract for procurement and installation of a WTS-4 was initiated February 1, 1980. Design work to upgrade the WTS-3 to a WTS-4, meeting the full requirements of the procurement specification, was completed in 1980 and all manufacturing activity, exclusive of the blades, was concluded in early July of this year. Final assembly is currently nearing completion and system testing has been initiated. Present plans are to install and operate the SVU in the early spring of 1982.

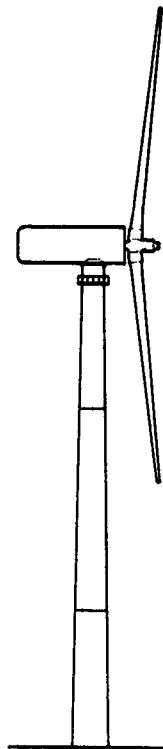
## SPECIFICATIONS

The WTS-4 specifications are shown in Figure 1.

- Rating — 4.0 megawatts
- Wind regime (at hub centerline)
  - Cut-in 6.9 m/s (15.4 mph)
  - Rated 15.1 m/s (33.9 mph)
  - Cut-out 27 m/s (60.4 mph)
- Life
  - 30 years
  - Low annual maintenance

FIGURE 1. WTS-4 SPECIFICATION

The operating range between cut-in and out-out was selected to maximize energy capture tailored to the Medicine Bow site. The characteristics of the machine are shown in Figure 2.



- Rotor
  - Diameter: 78.1 meters (256.4 ft)
  - Speed: 30 rpm
  - Two blades: filament-wound fiberglass
  - Downwind
  - Full-span pitch control
  - Free yaw
  - Teetered with delta-3
- Nacelle
  - Gearbox: Two-stage, 1:80
  - Generator: 1800 rpm, 60 Hz, synchronous
  - Control system: Digital, microcomputer, high reliability
  - Switchgear: Utility standard
  - Housing: Fully enclosed, ventilated
- Tower characteristics
  - Hub centerline height: 80 Meters (262 ft) AGL
  - Construction: Steel shell
  - Diameter: 12 ft. nominal

FIGURE 2. WTS-4 CHARACTERISTICS

The rotor diameter, 78.1 meters (256.4 feet), is identical to the Swedish WTS-3. The WTS-4 has many of the same components as the Swedish WTS-3. The major changes include a larger generator to accomplish 4 MWs and rotor operation at 30 rpm to accomplish the 60 Hz synchronous operation of the generator using the same gearbox. The tower and foundation are also of different design.

Features of the WTS-4 include the following:

- Dynamic force, moment, and torque decoupling of the rotor from support structures.
- Teeter hinge minimizes dynamic loading.
- Delta-3 control permits free yaw operation with accurate weather-vaning.

- Soft-mounted gearbox and fast control for high energy capture and smooth power quality during high gusty winds.
- 4.0 MW synchronous generator with 20% over-rate capability.
- Fully redundant hydraulic control pitch change system and completely autonomous emergency shutdown control system.
- Central electronic computer (nacelle mounted).
- Filament-wound, monolithic fiberglass blades.
- Full span pitch control for maximum control authority, energy capture and minimum drag above cut out velocity.
- Tall, slim, soft/soft tower minimizes turbulence loads, allows higher energy capture in high wind shear locations and provides seismic isolation.
- Fast pitch change rates for quick cut in, cut out operation and high power quality.
- Ramped cut in, cut out loading sequencing.
- High turbulence intensity foundation design.

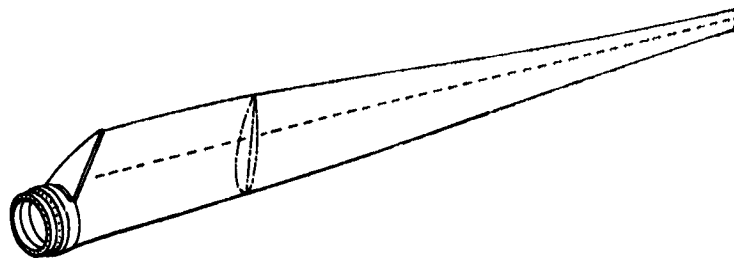
#### DESCRIPTION OF WTS-4 WIND TURBINE

The major components of the WTS-4 are common to most horizontal-axis wind turbines. They are the rotor, gearbox and generator mounted on a nacelle at the top of a tower. The rotor consists of two blades and a hub which contains the full span pitch change mechanism. The rotor is mounted to the shaft of the nacelle by means of a teeter pin which is tilted for Delta-3 effect. The nacelle is allowed to yaw freely at the top of the tower.

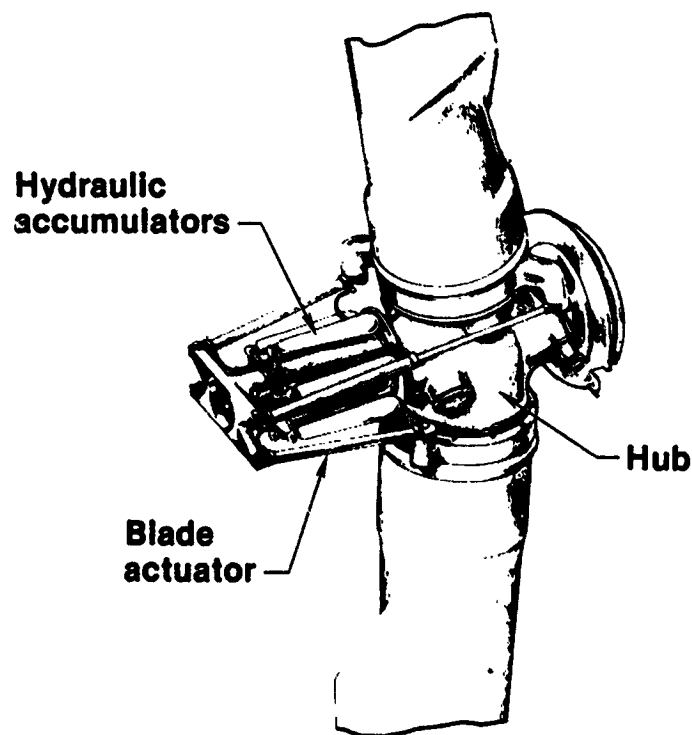
The blade is a 38 meter (125 ft) long, filament-wound, monolithic fiberglass structure as shown in Figure 3. Filament-wound fiberglass was selected for its low cost and high structural integrity that is resistant to environmental effects such as corrosion. At the root of the blade are steel retention rings which are mounted to a bearing on the hub allowing the blade to completely rotate in pitch.

The hub, shown in Figure 4, is a steel structure containing the teeter and blade bearings, the hydraulic control mechanism, pitch change actuation system and the emergency feather accumulators.

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**FIGURE 3. THE WTS-4 BLADE FABRICATED OF FILAMENT-WOUND FIBERGLASS FOR STRENGTH, LIGHT WEIGHT AND LONG LIFE**



**FIGURE 4. THE HUB, A STEEL FABRICATION CONTAINING THE TEETER BEARINGS AND PITCH CHANGE SYSTEM**

The nacelle is shown schematically in Figure 5. Shown are the relative locations of the gearbox, generator, and hydraulic supply system. The generator is provided by Ideal Electric of Mansfield, Ohio, and the gearbox by Thyssen Henschel of West Germany. The nacelle, provided by Karlskronavarvet of Sweden, mounts to the top of the tower by means of a cylindrical roller yaw bearing which allows the nacelle rotor assembly to freely rotate in yaw.



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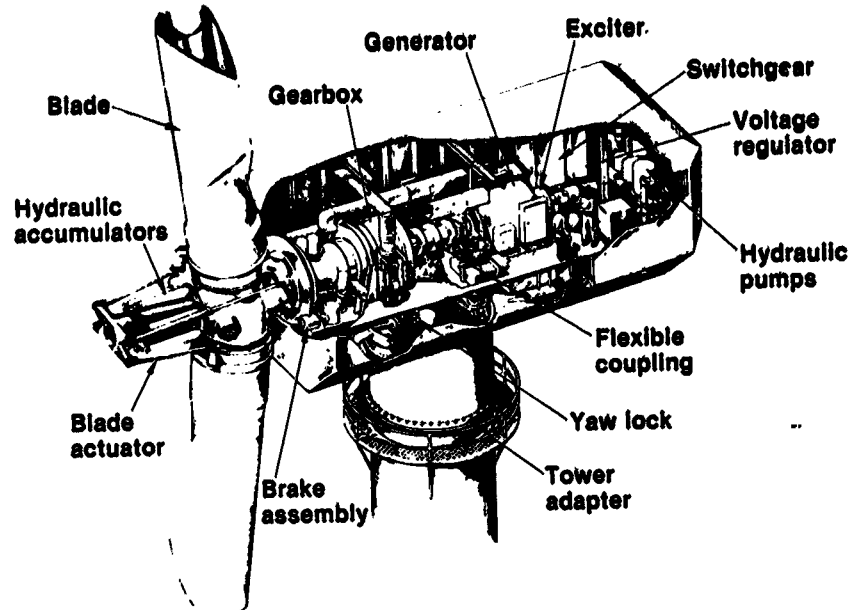


FIGURE 5. THE NACELLE CONTAINS THE DRIVE TRAIN  
AND GENERATOR MOUNTED ON THE BEDPLATE

The control system consists of microprocessors located in the nacelle and the base of the tower, as shown schematically in Figure 6. This system provides not only unattended operational capability, but also safety, maintenance, and diagnostic features. It allows operation from a nearby control building and has the capability of being operated from a remote station in Casper, Wyoming.

The tower, as shown in Figure 7, is a hollow steel tube provided by ITT Meyer Industries of Redwing, Minnesota and is fabricated of formed steel plates arranged in a twelve-sided tubular structure and seam-welded, similar to modern transmission tower construction. Cor-Ten steel was selected for its corrosion resistance and low maintenance. The tower contains an elevator, safety ladder, and cable trays for retaining power and control signal cables.

The foundation consists of a single caisson drilled pier construction 70 feet deep and 19 feet in diameter. This construction, shown in Figure 8, was selected as the most cost-effective foundation for the soil conditions at the site. One tower section is embedded in the foundation during construction with the above-ground sections being welded during tower erection. Site and construction work is being performed by Stearns-Roger of Denver, Colorado.

## OPERATION

Operation of the WTS-4 is automatic. A start and shutdown sequence is shown in Figure 9. Starting with the standby condition when the measured wind velocity reaches cut-in (the wind speed above which efficient power can be produced),

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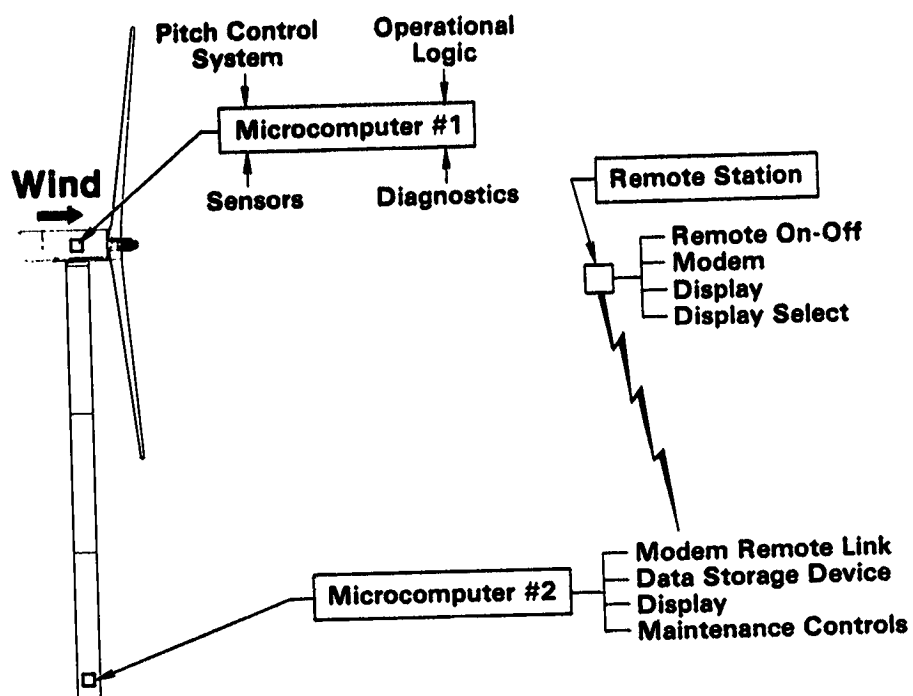


FIGURE 6. THE CONTROL SYSTEM PROVIDES UNATTENDED OPERATION, SAFETY, MAINTENANCE AND DIAGNOSTIC SYSTEMS

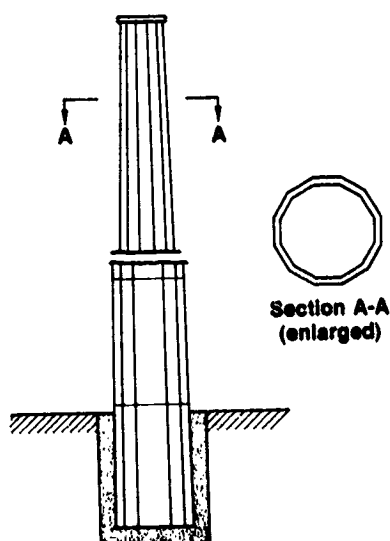


FIGURE 7. THE TOWER IS FABRICATED FROM COR-TEN STEEL FOR MINIMUM MAINTENANCE

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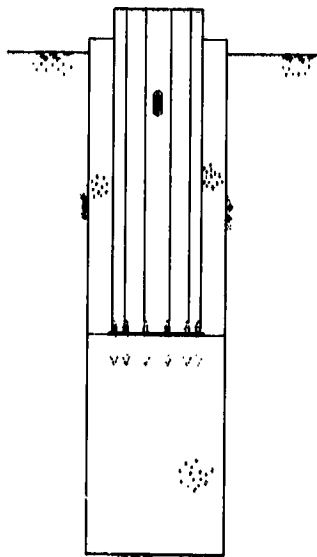


FIGURE 8. THE FOUNDATION WAS SELECTED FOR ITS COST EFFECTIVENESS FOR THE SOIL CONDITIONS AND HIGH TURBULENCE INTENSITY AT MEDICINE, BOW, WYOMING

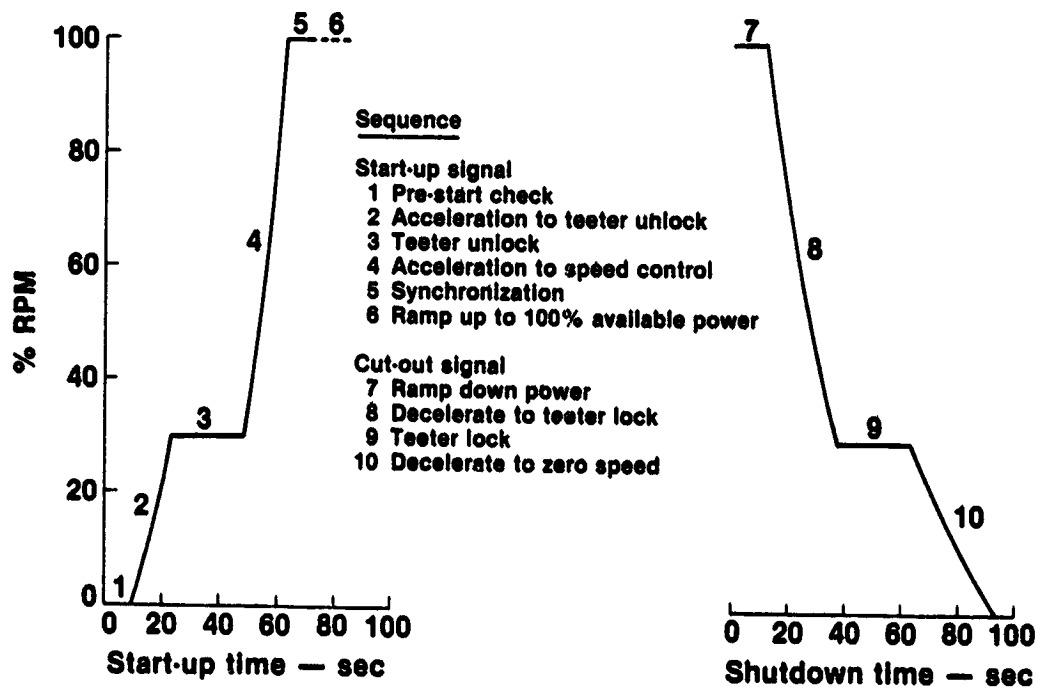


FIGURE 9. AUTOMATIC START-UP AND SHUTDOWN IS SCHEDULED FOR MAXIMUM ENERGY CAPTURE

the control system automatically goes through prestart check to ensure that all normal and emergency features are operational. The blades are then positioned in pitch to achieve maximum rotational acceleration. As rotor rpm increases, the control system controls the pitch to pause at 10 rpm at which time the teeter locks are deactivated. The rotor is then allowed to accelerate to 30 rpm, at which time the speed is controlled by operation of the pitch change system at synchronous speed. The control automatically synchronizes and connects the generator with the grid. The pitch change system is then controlled to achieve 100% of available power or the maximum rating of the generator.

When the winds achieve cut-out velocity (a wind velocity chosen for energy capture and safety reasons), the control system automatically ramps down the power, disengages the generator from the line, implements the teeter locks at approximately 10 rpm, and decelerates to zero speed. When the unit is not operating, the blades are feathered vertically and the wind turbine automatically weather-vanes downwind.

## STATUS

The WTS-4 wind turbine design is complete and the components are being manufactured and assembled. Fabrication of the blades is under way. Figure 10 shows the completed spar of the first blade. The nacelle is in the final assembly stages in Sweden and the control system software is being checked out.

The nacelle assembly, prior to having the cover installed, is shown in Figure 11. The tower has completed its factory fabrication and has been delivered to the site in four sections. It will be welded together during erection. The hole for the caisson foundation has been drilled and rebar is being installed prior to pouring the concrete. All the hardware and components will be on-site in early 1982 ready for erection.

The WTS-4 is an advanced design of a large horizontal-axis machine and lends itself to numerous site applications. It has been optimized for high wind sites where wind energy holds the most promise of economical power production. Plans are well advanced to fabricate and install 20 such machines in Hawaii as part of a program with Windfarms Limited of San Francisco. The Kahuku Point project will supply electricity to the Hawaiian Electric Company. A letter of intent has also been signed with Southern California Edison to install five units at San Geronio Pass, California.

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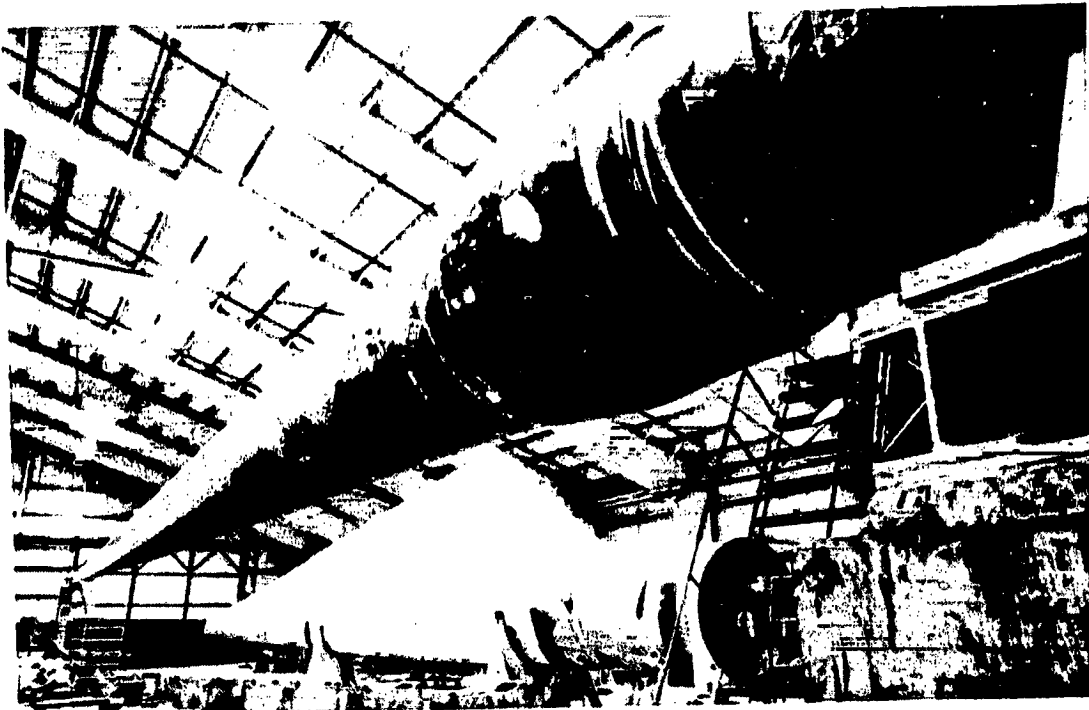


FIGURE 10. COMPLETED FILAMENT-WOUND SPAR OF THE FIRST  
WTS-4 BLADE

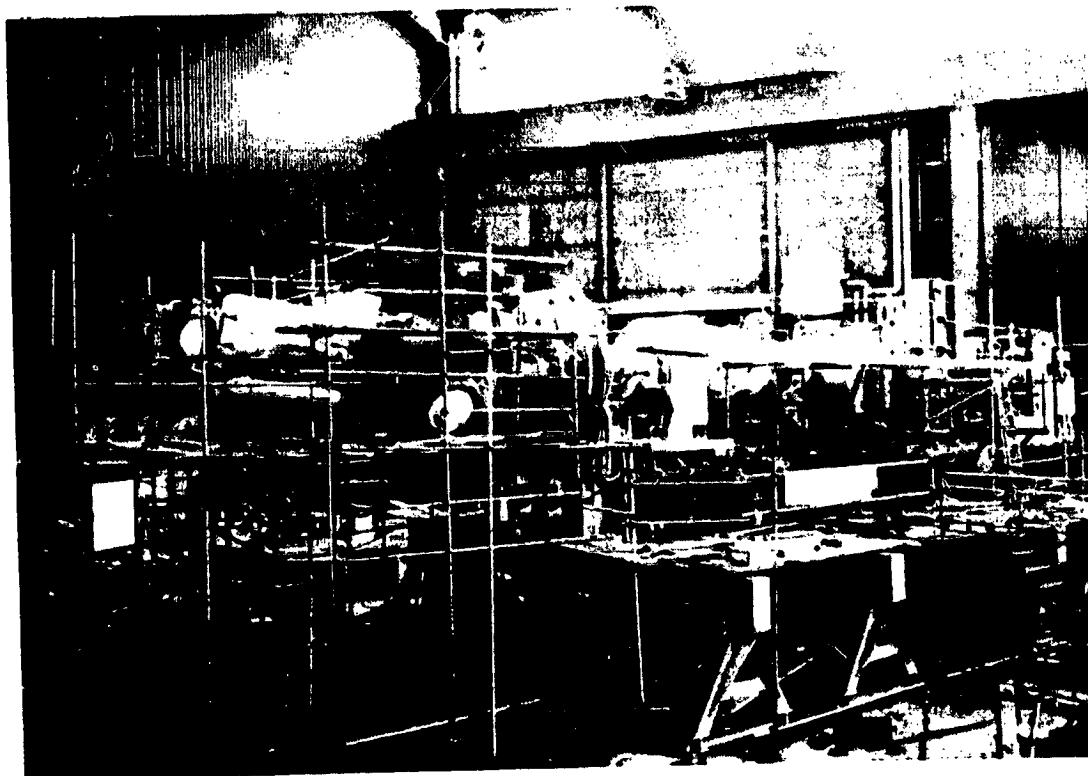


FIGURE 11. NACELLE IN FINAL STAGES OF ASSEMBLY

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## QUESTIONS AND ANSWERS

R. J. Bussolari

From: R. Barton

Q: How does the predicted SVU sound compare with the Mod-1 or Mod-2 measurements?

A: *Although no prediction methodology has been developed for wind turbine noise, it is expected that the noise of the WTS-4 would be less than that of the Mod-1 and probably greater than that of the Mod-2, which appears to be very quiet.*

From: A. Saunders

Q: In a power down sequence, exactly what generates the signal to disconnect from the grid?

A: *This is handled by the control system timing and sequencing during the controlled "power down."*

From: R. G. Pratt

Q: Why would there not be an acoustical "thump" as the Mod-1 has?

A: *The Mod-1 has a large wake defect from the truss tower, a stiff rotor (not teetered) and metal blades. The acoustic effect from the tower wake is expected to be low on the WTS-4.*

From: S. C. Rybak

Q: How does the Delta-3 optimize free yaw behavior?

A: *This is done by compensating the change in blade angle of attack due to teetering in a wind shear.*

From: H. Standard

Q: Can the machine withstand maximum gust loading with blades unfeathered?

A: Yes.

From: A. Swift, Jr.

Q: What is the  $\delta_3$  angle? Do the blades perform about the  $\delta_3$  axis as a pair or singly?

A: *The angle is  $30^\circ$ . The blades operate as a pair.*

R. J. Bussolari (continued)

From: G. Schanzonbach

- Q: 1) What type (model no.) of microprocessor was used in the central system in the nacelle and on the ground?  
2) How many lines of code are there in the control system software?

- A: 1) *The microprocessor model was Intel-ISBC 86/12A.*  
2) *There are about 9,000 lines of code in the control system software.*

From: Anonymous

- Q: What are the maximum wind speeds assumed in the design at hub height for 1) maximum gust during operation, and 2) maximum gust during hurricane or tornado loading?

- A: 1) *60 mph at cut-out.*  
2) *125 mph for hurricane, not tornado.*

From: A. S. Jagtiani

- Q: What is the approximate cost per unit? How many utilities have shown any interest?

- A: *Four to five million dollars in production quantities. A number of utilities have shown interest but none have placed any orders.*

From: F. March

- Q: How is the tower anchored within the foundation pit?

- A: *Concrete is both on the inside and outside of the embedded section of the tower.*

From: L. P. Rowley

- Q: Can the accumulator feather the blades from an overspeed condition in a high wind speed? Is this a design case?

- A: *Yes! Yes, this is one of the design drivers.*

From: R. B. Stephens

- Q: Is there any literature on the machine?

- A: *Yes, we have brochures available. Write to Hamilton Standard, Windsor Locks, Connecticut.*

R. J. Bussolari (continued)

From: Anonymous

Q: What role did the National Swedish Energy Board have in the development of the WTS-3 and WTS-4?

A: *The role of the N.E. is similar to the DOE in the U.S. It is sponsoring the WTS-3 program in Sweden.*

From: S. Chase

Q: Will a crane or the tower be used to raise the nacelle and blades?

A: *A gallows frame will be used.*

From: W. Lucas

Q: How dependent on soil conditions is the use of the single pier tower foundation (i.e. would you use a different concept for sandy-clay soil)?

A: *It depends on the exact quantitative evaluation of the soil. Generally, this type of foundation would be good in clay.*

From: J. I. Lerner

Q: What type of failure modes analysis have you been performing?

A: *An extensive FMEA (failure, modes and effect analysis) was performed.*



THE 80 MEGAWATT WIND POWER PROJECT  
AT KAHUKU POINT, HAWAII

R.R. Laessig  
Vice President-Engineering  
Windfarms, Ltd.  
San Francisco, CA 94111

Windfarms Ltd. is developing the two largest wind energy projects in the world. Designed to produce 80 megawatts at Kahuku Point, Hawaii and 350 megawatts in Solano County, California, these projects will be the prototypes for future large-scale wind energy installations throughout the world.

80 MEGAWATT WIND POWER PROJECT AT KAHUKU POINT, HAWAII

Location

The site for this project is the Kahuku Area on the northern tip of Oahu, Hawaii (Fig. 1). This location receives consistent northeast trade winds approximately 80% of the year.

Although Oahu is not the largest of the Hawaiian Islands, it contains over 90% of the state's population and has the highest electrical consumption. The state's largest city, Honolulu, is located on the south side of Oahu, which is on the opposite side of the island from the project area.

The site comprises about 2,100 acres, including three ridges which slope upward from the coast toward Mt. Kawela to an approximate elevation of 1,000 ft. These slopes increase the velocity of the prevailing

trade winds. Due to the wind's intensity, this area of Oahu is sparsely populated and contains less than 3% of the island's inhabitants.

Currently, Hawaiian Electric Company's (HECO) 1300-megawatt system is almost totally dependent on oil-fired generating plants. The annual fuel consumption is approximately 10 million barrels of oil. Having no petroleum deposits in the State of Hawaii, all oil must be imported at considerable expense adding substantially to the state's electricity costs.

Energetic winds, the high cost of fossil fuel, the support of the state government and the Hawaiian people make the northeast coast of Oahu one of the most desirable locations for the development of a major wind energy installation.

#### Project Description

Twenty machines with a nameplate capacity of 4 megawatts each will be placed on the Davis, Opana, and the Waialeale Ridges. This area is owned by the Campbell Estate, and part of the Waialeale Ridge by the State of Hawaii. It is presently used for training purposes by the U. S. Army which has a long-term lease that will expire in 1983. The renewed lease will contain provisions to permit the coexistence of the wind farm and the military training range.

The site map (Fig. 2) shows the arrangement of the machines and the road system that will be built for installation and maintenance of these machines.

The project will be developed in two phases:

The first phase includes six machines on Davis Ridge. Installation is expected to start by the middle of 1983 with commercial operations starting near the end of the same year. The transmission line used to transmit power to the HECO system will be the existing 46 kV transmission line on the north shore of Oahu. This line has a capacity of 22.5 megawatts and, therefore, is not large enough to take the 80 MW production of the entire wind farm.

The fourteen machines in the second phase will be installed in the beginning of 1984 with all machines expected to reach commercial operation by 1985. Upon completion of the two phases, the power of the entire project will be carried by a newly installed 20-mile long 138 kV transmission line from the existing Kuilima Substation on the north portion of Davis Ridge to the Wahiawa Substation.

### The Wind Turbine Generator

The WTG used in this project will be the Hamilton Standard WTS-4, a machine that will be installed later this year in the Medicine Bow Project and in Sweden. This machine has a rating of 4 megawatts at 34 mph with a rotor diameter of 260 ft. and a tower height of 250 ft. The machine is equipped with a downwind rotor and its characteristics are shown in Fig. 3.

A step-up transformer is used on each machine which increases the voltage of the generator (4160 volts) to an intermediate voltage of 46 kV. The 46 kV line from each ridge will be brought into a switchyard located near the present Kuilima Substation where all the switching and safety equipment is located. For phase I, the power will be transferred directly to the existing 46 kV transmission line, while the 138 kV transmission line will be used for phase II.

All wiring within the wind farm will be underground. This assures that the local environment will be disturbed as little as possible and may also increase local acceptance of the project.

### Land Acquisition

In July of 1980, Windfarms entered into a detailed agreement with the Campbell Estate, the owner of the land. Under the terms of this agreement, Windfarms is granted exclusive prospecting rights over the Estate's 2,100 acres. This allows Windfarms to conduct wind measurements and other meteorological work to determine the best sites for locating the turbine generators. It also allows Windfarms to select sites and do preliminary

meteorological and topographical work at the sites. After all sites have been clearly established, the Estate has agreed to grant Windfarms a separate lease of 2 acres for each generator site and easements for the ingress and egress and auxiliary buildings.

Many negotiations were necessary with the Campbell Estate and the U.S. Army which presently uses this area as a training ground. The U.S. Army has taken a very positive view of this wind power plant and a mutually acceptable way has been found to install the machines at the best wind location without impairing the U.S. Army's field training area.

#### Power Purchase Agreement

In July of 1980, Windfarms Ltd. and HECO entered into a Power Purchase Agreement in which HECO agrees to purchase all energy generated by the Project during the next 25 years. The price paid by HECO per kilowatt hour generated will be equal to its average cost per kilowatt hour during the preceding two month period. In addition, the Power Purchase Agreement specifies voltage and frequency requirements. Stability criteria are also an important factor, and preliminary calculations have been made to show that 80 megawatts on the present Hawaiian grid does not affect the stability of the grid. Final stability analyses will be presented in a future paper.

#### Meteorological Work

A comprehensive meteorological program has been launched by Windfarms to accurately determine the area's wind resource and the resulting energy output of the completed wind farm. After the installation of the 107-meter and 80-meter wind towers on the Davis Ridge, two extensive field services were conducted using kites and mobile equipment which allowed the project meteorologists to categorize each ridge and correlate it with the long-term measurements gathered by the Opana Ridge instrumentation and the Livermore Laboratories data.

Two additional towers will be installed at the Opana and Waialeale Ridges as soon as the permitting process is completed.

### Maintenance and Control Building

The switchyard and the maintenance and control facilities will be located near the Kuilima Substation. The control building will house the control center of the wind farm and will be the single interface point of the HECO system dispatcher and the wind farm. All parts required for routine and emergency maintenance will be stored in the maintenance building.

### Transmission of Electric Power

The power from the first phase of the project will be carried by a 46 kV power line which presently connects the north shore of Oahu to the HECO grid. This transmission line is large enough to take 22.5 megawatts (26 MVA). The Kuilima Substation will be used as a tie-in point to this transmission line.

For the second phase of the project, a 138 kV transmission line, approximately 20 miles long, is planned which will connect the Kuilima Substation with the Wahiawa Substation. Several routings have been proposed for this line. Minimizing the environmental impact and interferences with the training area of the U.S Army were the two determining factors for the final routing of this line (Fig. 4).

The transmission line begins at the Kuilima Substation, and will be routed through a gulch to avoid visibility from the highway. It then proceeds in an approximately southern direction through inaccessible mountain territory, and then runs to the west, terminating at the Wahiawa Substation. The transmission line towers that are located in the southern mountain range are not accessible by road and will have to be placed and maintained by helicopter.

In order to establish a back-up line, the 46 kV line connections at the Kuilima Substation will be made permanent. The control system will limit the output of the wind farm to 22.5 MW at times when the 138 kV line is not operational or during maintenance periods.

This power line has been surveyed and tower locations have been selected. April 1984 is the anticipated completion date.

The Hawaiian Electric Company will build and maintain this power line as a subcontractor for Windfarms.

The metering devices used to determine the power delivered from the wind farm to the HECO grid will be located at the Wahiawa Substation, while the power delivered during phase I will be measured at the Kuilima Substation.

#### Environmental Impact Statement

In addition to selecting the locations of the machines and planning for the 138 kV transmission line, the current activity includes the preparation of the Environmental Impact Statement. For this purpose, several local experts were hired to study the archeological, botanical, zoological, socio-economic, and the electro-magnetic interference impacts of the wind farm and transmission line to the area. This work is being conducted by the Bechtel Power Corporation in Norwalk, California, and a first environmental assessment was filed in June 1981. It is hoped that, by the beginning of 1982, all permits will be obtained to start site preparation, road construction, power lines, switchyards, and control maintenance buildings.

A list of required permits and issuing agencies is shown in Fig. 5.

#### Costs and Schedule

Negotiations about the final cost of the project are underway and it is still too early to publish a final figure. Currently it is expected that the project cost will be in excess of \$250 million. Several cost items will be discussed that are usually not carried in present projections.

A major expense is the cost of interest during construction. This cost for the present project is approximately \$80 million. A further substantial expense item is the cost of the transmission line. It is estimated that the cost of the transmission line will be in excess of \$500,000 per machine, or over \$10 million for this project.

Furthermore, costs such as land and Land Agreements, Environmental Impact Statements, Power Purchase Agreements, and Maintenance Agreements are escalating the cost of the wind farm beyond what was anticipated. It is important that these costs be considered in future installation cost projections on similar projects.

For the site of Hawaii, the cost of the transportation of the equipment and all auxiliary hardware to the island, and then from the port of entry to the project sites is a very significant addition to the total installation cost; they are enhanced by the non-availability of large cranes and insufficient port facilities on the north shore of Oahu.

The installation of the WTGs is scheduled for the beginning of 1983 and commercial operation of the entire wind farm is expected beginning in 1985.

#### THE BIG ISLAND PROJECT

A 4 MW project is being developed for installation on the Island of Hawaii (Big Island). It is connected into the Hawaii Electric Light Company (HELCO) grid at the Kamea Range (Fig. 6).

A Land Agreement was made with the Parker Ranch, owner of the land in this area. The Power Purchase Agreement has been executed with HELCO specifying the amount and quality of power to be delivered to the HELCO system.

Two meteorological towers have been installed near the sites and meteorological data are presently being obtained. Concurrently, preliminary sites were established and geological and topographical work was performed to validate the viability of the established sites (Fig. 7).

The power will be collected from the generators at 4160 volts and then a single step-up transformer will increase the voltage to 34.5 kV, the voltage of the existing transmission line.

The present schedule calls for start of commercial operation at the end of 1982 with a total system cost of less than \$12 million.

#### SOLANO COUNTY PROJECT

A 350 MW wind power project is being planned by Windfarms Ltd. near San Francisco, California.

##### Location

The project is located in the hills south of Vallejo in a parcel bounded by Interstate 80, 780, and 680 in the rolling hills of Solano County (Fig. 8).

##### Project Description

A Letter of Agreement has been signed with the Pacific Gas and Electric Company (PGandE) which outlines location, size, and power requirements of this wind power installation. The total installation will include approximately 100 machines of various designs.

The first 90 megawatts of this wind farm will be connected to an existing 115 kV line that transverses diagonally through the area.

The electrical interconnection line of this farm will be underground at 20 kV, similar to the Hawaiian project. Phase I power will be collected at two switchyards, stepped up, and then transmitted into the existing 115 kV lines (45 MW each).

A preliminary layout of phase I of this project is shown in Fig. 9.



Additional transmission line capacity will be required when the project exceeds 90 megawatts. This is projected for 1986. PGandE is planning the new transmission line in order to transport 260 megawatts out of this area into the PGandE grid and satisfy other local power requirements.

Preliminary WTG sites have been selected for phase I of this project (90 megawatts) and meteorological studies have started with preliminary surveys of the site areas by kite measurements.

Two temporary 10-meter towers have been erected and two 100-meter towers are projected to be installed as soon as permits and equipment are available.

Aside from the meteorological activities and preliminary site planning, the current thrust of this project is completing the Environmental Impact Statement, grading plans, and the layout and routing of roads and electrical power lines are being developed.

The Environmental Assessment is progressing with the assistance of Dan Coleman Associates. The first geological survey has been completed by Earth Sciences, Inc.

The present schedule projects the start of installation of the first portion of phase I by mid-1983 and will proceed on an installed power schedule shown in Fig. 10.

The Solano Project is the first large wind farm within the continental United States and will serve as an excellent example for integration of wind power into large continental grid systems.

#### DESIRABLE FEATURES OF FUTURE WIND TURBINE GENERATORS

The wind farm installations discussed in this paper indicate that wind power is entering a new phase. The technology developed and gathered by DOE, NASA, and private industry is being used to produce large and reliable wind power machines that fit the use for utility-type wind power production.

It is, therefore, appropriate to make a few remarks on desirable characteristics of these wind machines.

#### Low Equipment Cost

The tremendous cost of the currently available machines makes it mandatory to use them in connection with high average wind velocities and with utilities having high electricity production costs. Present tax credits are very helpful but it is absolutely necessary to reduce the cost of future machines to a level where the kilowatt hour can be produced below 5 cents, including all installation, service, and finance costs.

#### Optimum Machine Size

The considerable cost of site preparation, land costs, transportation, and other auxiliary costs require that the machines be sized as large as feasible and that the size optimization take into account a realistic assessment of these costs based on present requirements.

The recent trend which we have seen in the MOD-5 studies confirms this point and we hope that future developments will strengthen the economic viability of wind power systems for areas with lower wind velocities and for utilities where the avoided cost of electricity is not extremely high.

#### Low Erection Cost

The previous paragraph underlines the necessity of lowering erection costs of the WTGs and also the necessity of reducing erection time in order to minimize the cost of interest during construction. New cost effective methods have to be found especially for the erection of machine clusters such as those described in this paper.

### Transportation Costs

The planning of our Hawaiian installation has shown that transportation has a significant impact on the overall cost of the project. The main problems here are overall dimension and overall weight.

The local non-availability of large cranes is a very important factor. Road clearances of over 14 feet can also be a detracting requirement. Therefore, the limitation of size and weight is an important design parameter which should be considered in order to make the transportation and installation more cost effective and less time consuming.

### Reliability/Maintenance

From the standpoint of the user of a wind installation, the most unestablished items in his equation are the cost of maintenance and the outage time of the equipment for this maintenance. It is most important that the equipment be designed with a very high availability factor and, at the same time, a very low maintenance cost. That means that simplicity of design, a minimum of parts, and good accessibility for all maintenance should be high priority items.

A simple and cost effective maintenance program for a 30-year period has to be established.

### Environmental Impact

In the past few years, Environmental Impact Statements have filled many months at the beginning of a power plant project. It is important that wind turbines are being designed in a way to have minimum impact on the environment. In particular, this includes the creation of noise and visual impact. Another large portion of this impact is the electromagnetic interference that affects TV as well as communication links.

## Life

In the immediate future where privately-owned wind farms will be more predominant, the life of the machine will be a very important factor for financing the entire project. It will be a long time before life projections on machines can be based on experience. It is, therefore, especially important that the early machines are of a very long life expectancy and operate in a reliable and predictable fashion.

We are presently entering a new phase of wind turbine generator development that reaches beyond the technical feasibility stage of the first machines. It is now our responsibility to prove that wind farms can be built and operated as long life reliable power sources and that the sight of large wind power farms should be as common for future generations as the many thousands of power generating and water pumping machines existing in the early part of this century.

ORIGINAL PLANS  
OF POOR QUALITY

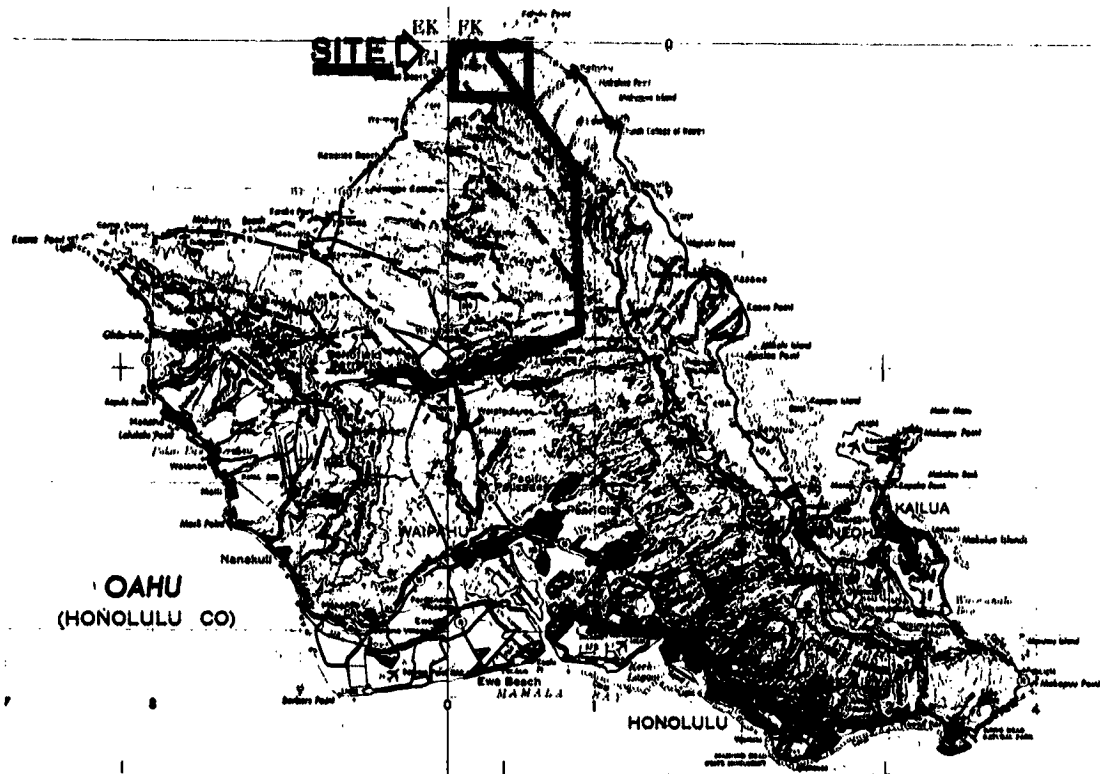


Fig. 1

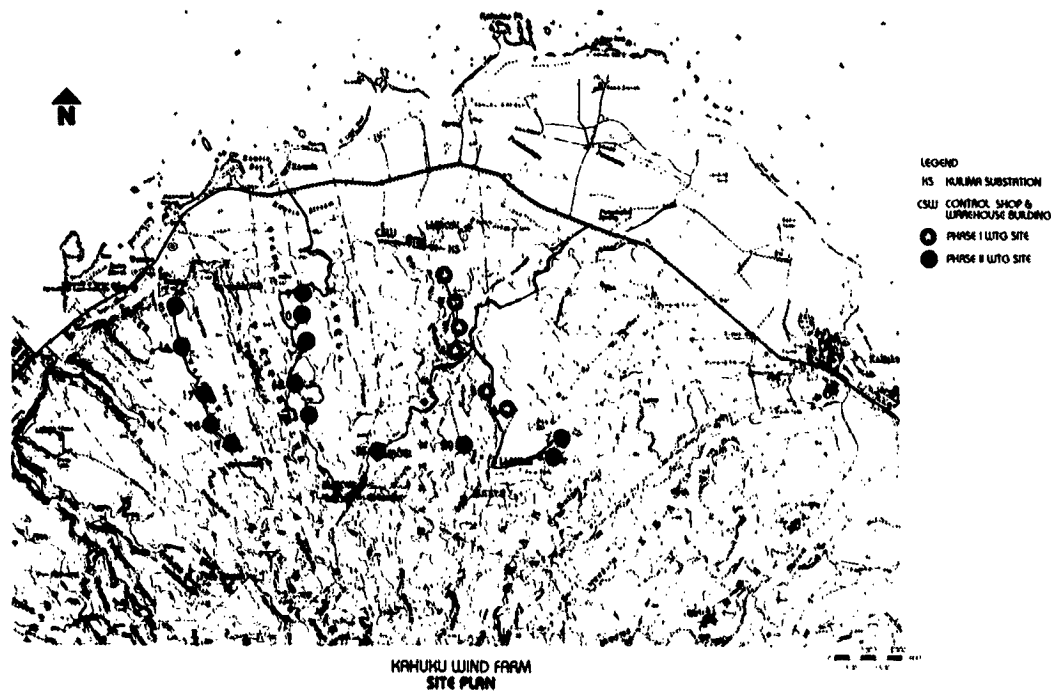


Fig. 2

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KAHUKU POINT  
WIND FARM SYSTEM CHARACTERISTICS

POWER	80 MW
YEARLY ENERGY OUTPUT	$>300 \times 10^6$ KWhr/YEAR
WTG	20 HAMILTON STANDARD WTS-4
NAMEPLATE RATING	4 MW
ROTOR DIAMETER	80M
HUB HEIGHT	80M
RPM/ROTOR DIRECTION	30 RPM/DOWNWIND
TOTAL WEIGHT	407 TONS
TOWER WEIGHT	200 TONS
NACELLE & ROTOR	207 TONS

TRANSMISSION LINE

1ST PHASE INSTALLATION	6 WTGs
22.5 MW/46 KV TO EXISTING KUILIMA SUBSTATION	
2ND PHASE INSTALLATION	14 WTGs
80 MW/138 KV TO WAHIAWA SUBSTATION (20 MI.)	

LOCATION: DAVIS, OPAHA & WAILEE RIDGES

SUBSTATION & SWITCHYARD: AT KUILIMA SUBSTATION

Fig. 3

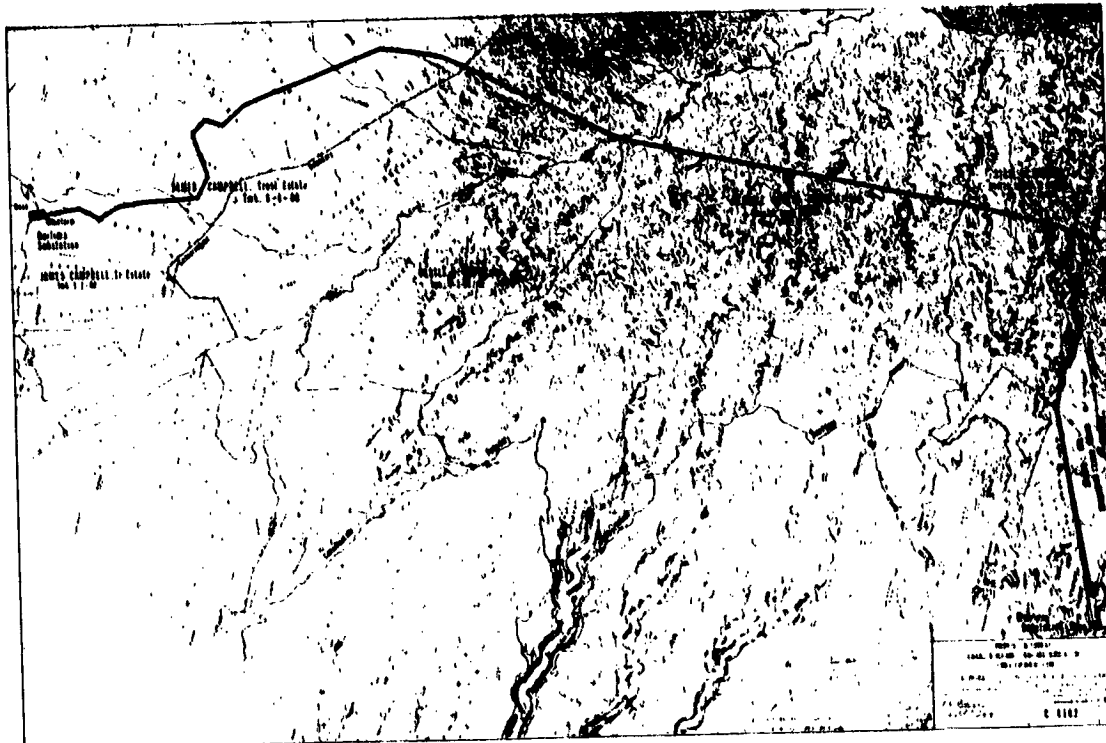


Fig. 4

## REQUIRED PERMITS

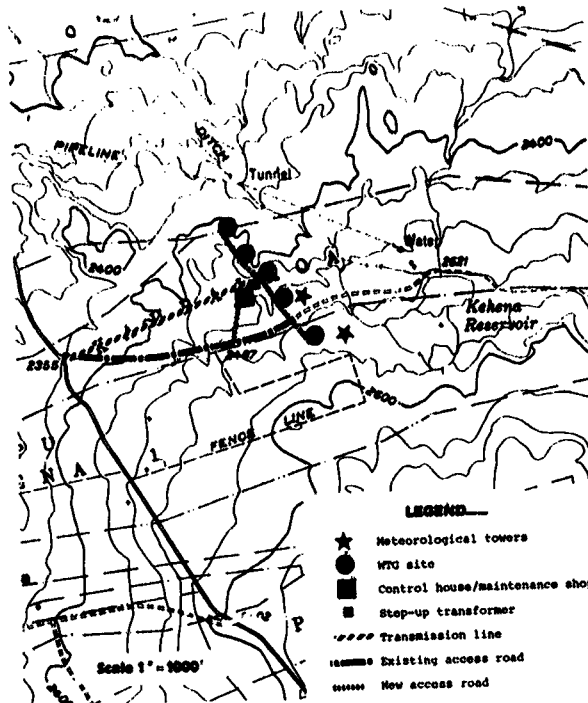
**Fig. 5**



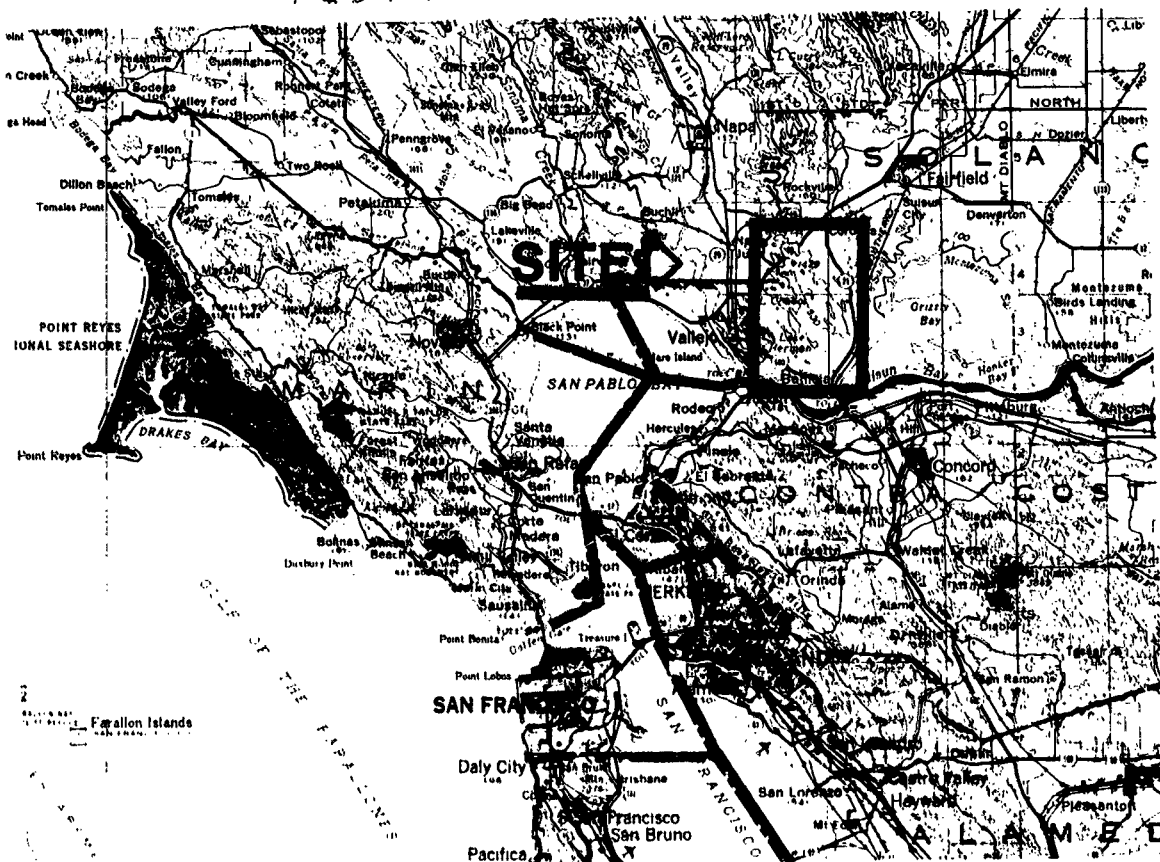
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# **BIG ISLAND WINDFARM**

## **Preliminary Plan**



**Fig. 7**



**Fig. 8**



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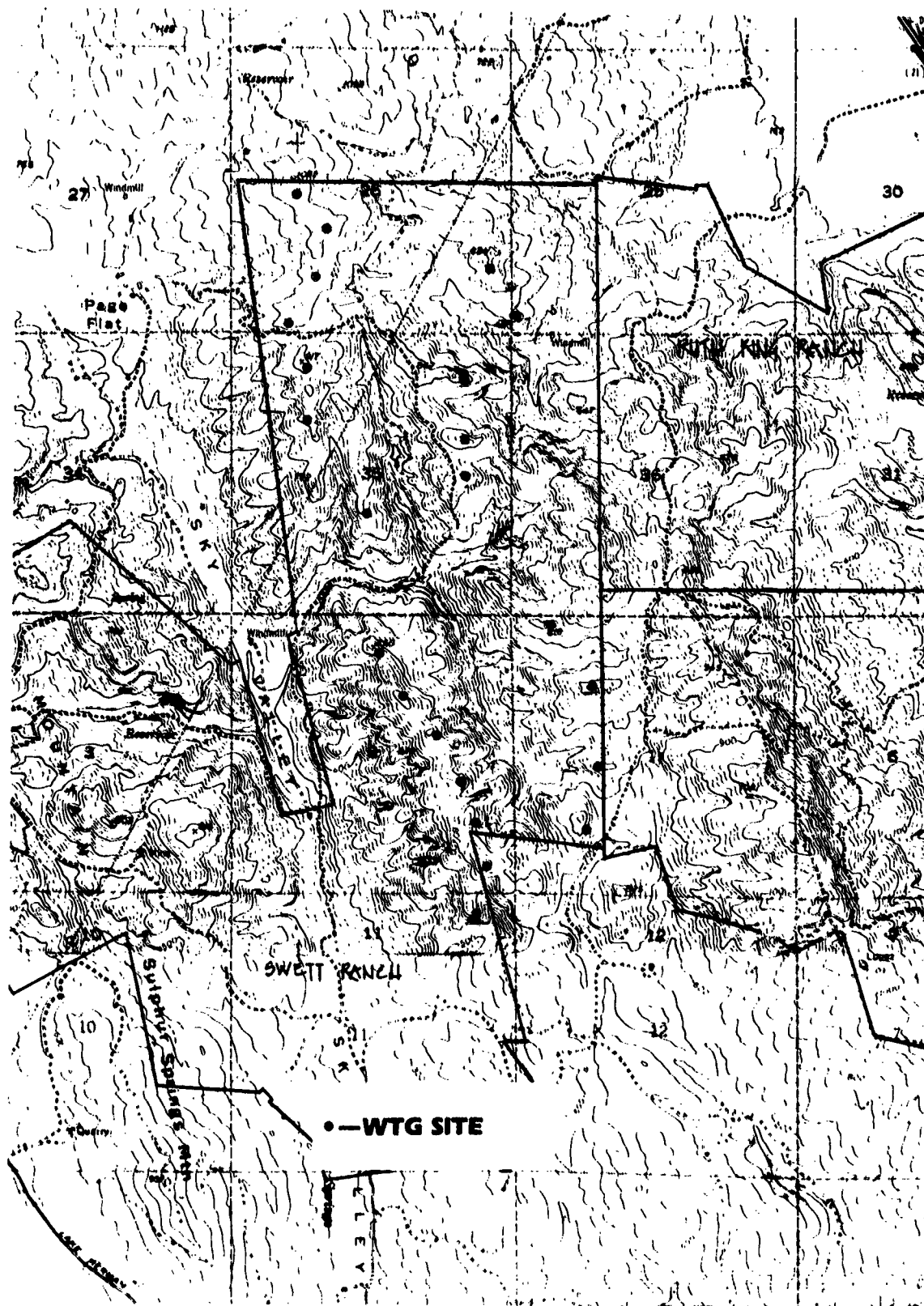


Fig. 9

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## **SOLANO WIND FARM PROJECTED CAPACITY**

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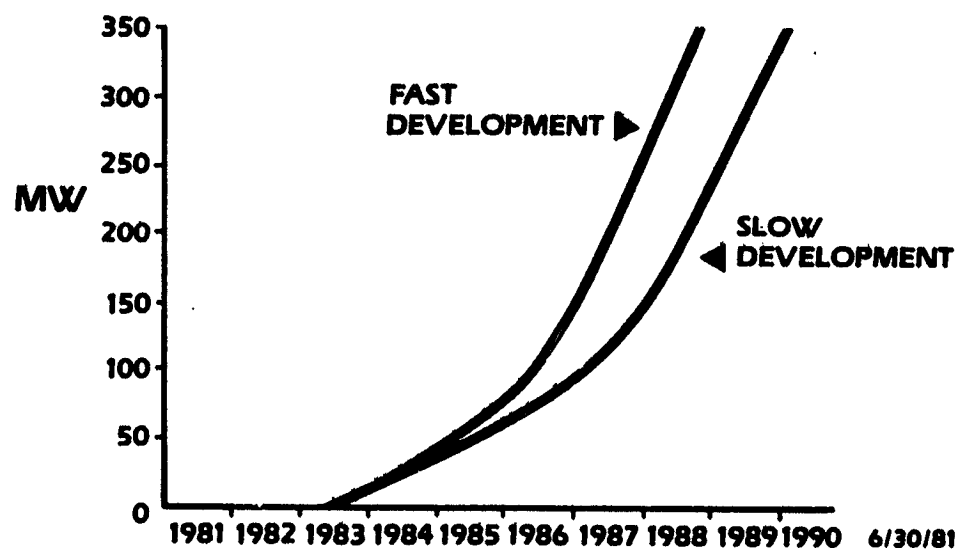


Fig. 10

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79  
P711

## QUESTIONS AND ANSWERS

R. Laessig

From: J. Glasgow

Q: What machine do you plan for your small Hawaii 4 MW installation?-----

A: *This has not been decided yet. The selection will be made shortly.*

From: G. Biro

- Q: 1) How much is the real estate value (Hawaii, Solano)?  
2) How much are the energy credit and tax benefits to the power company?  
3) What is the minimum distance on a ridge in Hawaii?

A: 3) *1000 ft normal to wind; 3000 to 5000 ft in wind direction.*

From: P. Simpson

- Q: 1) What wind measurements have been made at the various sites?  
2) What is the annual mean wind speed at machine hub height?  
3) What is the estimated total cost of providing access to the sites of the machines in the 80 MW farm?  
4) What is the estimated total cost of transportation?

A: 1) *At Kahuku Point, 107 m and 80 m towers, measurements have been taken since April 1981. At the Opana 30 ft tower they have been taken for 5 years. In Solano County measurement taking will begin in August at two 10 m and two 100 m towers and 3 measurement sites of PG&E.*  
2) *It varies from site to site.*

From: Anonymous

- Q: 1) What arrangement has been made with the property owners for use of their land?  
2) What price are you being paid for the electricity?

A: 1) *The land for phase 1 is owned by PG&E.*  
2) *The price of electricity is presently being negotiated.*

From: D. Bain

- Q: 1) For the Hawaii 80 MW project, what is the cost of obtaining the needed permits?  
2) How is long term wind access assured?  
3) What are the project start and completion dates for hardware installation?

R. Laessig (continued)

- A: 1) Approximately \$1 M.  
2) The annual energy production is  $17 \times 10^6$  Kwhr per machine at 100% availability.  
3) Start of commercial operation is planned for mid-1983, completion for 1985.

From: Anonymous

Q: How many total miles of transmission line are you installing for \$12.4 M? What is the separation distance between machines?

A: The cost of the 20 mile 138 kv transmission line for phase 2 is \$7.8 M; other costs are for phase 1 connection and other required improvements.

From: B. Masse

Q: What is the cost of electricity in Hawaii? What will be the cost with the wind farms?

A: The cost of electricity is presently approximately \$0.06 per Kwhr. Since we are only providing less than 10% of the entire energy, the effect will not be pronounced.

From: A. Swift, Jr.

Q: How did you attract sufficient private investors?

A: Through investment banking corporations.

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LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Electric Utility Activities

Session Chairman - F. R. Goodman (Electric Power Research Institute)

"An Overview of Large Wind Turbine Tests by Electric Utilities"

W. A. Vachon

D. Schiff

(Arthur D. Little, Inc.)

"Utility Experience with Two Demonstration Wind Turbine Generators"

M. C. Wehrey

(Southern California Edison Company)

"WTS-4 System Verification Unit for Wind/Hydroelectric Integration Study"

A. W. Watts

(U.S. Bureau of Reclamation)

"Initial Utility Experience with Cluster of Three Mod-2 Wind Turbine Systems"

D. B. Seely

E. J. Warchol

N. G. Butler

S. Ciranny

(Bonneville Power Administration)

"A Review of Utility Issues for the Integration of Wind Electric Generation"

T. W. Reddoch

P. R. Barnes

(Oak Ridge National Laboratory)

"Economics of Wind Energy for Utilities"

T. F. McCabe

M. Goldenblatt

(JBF Scientific Corporation)

## AN OVERVIEW OF LARGE WIND TURBINE TESTS BY ELECTRIC UTILITIES

by

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20 Acorn Park  
Cambridge, Massachusetts 02140

## ABSTRACT

A summary of recent plans and experiences on current large wind turbine (WT) tests being conducted by electric utilities is provided. The test programs discussed do not include federal research and development (R&D) programs, many of which are also being conducted in conjunction with electric utilities. The information presented is being assembled in a project, funded by the Electric Power Research Institute (EPRI), the objective of which is to provide electric utilities with timely summaries of test performance on key large wind turbines. A summary of key tests, test instrumentation, and recent results and plans is given. During the past year, many of the utility test programs initiated have encountered test difficulties that required specific WT design changes. However, test results to date continue to indicate that long-term machine performance and cost-effectiveness are achievable.

## INTRODUCTION

In the past two to three years, several electric utilities have initiated large WT test programs aimed at obtaining "hands-on" experience with large wind machines interconnected with their networks [1-3]. These programs have been conducted in parallel with--and often complementary to--the federal large WT development and test programs. This paper summarizes findings from a project sponsored by EPRI, which has as an objective the assessment of results from both federal and privately funded large\* WT tests and to communicate key results to the electric utility industry. Thus far, three reports have been written on this project and are available from EPRI [4-6].

The major sources of data for this project are:

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\*Large WT's are those with  $P_{rated} \geq 100$  kW.

- Federal R&D projects dealing with large WT's;
- Private manufacturers of large WT's; and
- Electric utilities that are installing large WT's.

The material discussed in this report summarizes key aspects of programs in which electric utilities have installed WT's. The major programs discussed are being conducted in the United States, Canada, and Denmark.

#### OBJECTIVES OF WT TESTS

The major objectives of the current large WT tests being conducted by electric utilities include the following:

- Obtain "hands-on" operational experience;
- Become familiar with WT technology and economics,
- Measure the impacts of machines on the network;
- Determine long-term machine reliability;
- Examine interconnection issues and problems; and
- Determine long-term operation and maintenance (O&M) costs.

The goal of some utility WT tests is to realize only a limited number of these objectives; the goal of others is to address all of them. The key elements in each utility test are described in the following sections.

#### KEY LARGE WT TESTS

Table 1 provides a summary of the 11 key utility large WT tests being carried out by 8 utilities in the U.S., Canada, and Denmark. The tests involve eight different WT's, although on first examination, it appears that there are only seven WT's. However, the two machines being tested by ELSAM, the Danish utility, have different rotor designs, although they have the same dimensions and configuration.

Only 3 of the 11 machines are vertical-axis wind turbines (VAWT's) of the Darrieus design. The remaining eight are two and three-bladed horizontal-axis wind turbines (HAWT's). Even though past studies, aimed at projecting the cost of energy from WT's, identified multi-megawatt machines as the most cost-effective approach, most of the test machines shown in Table 1 (7 of 11) fall in the medium-scale range (i.e.,  $100 \text{ kW} \leq P_{rated} < 1,000 \text{ kW}$ ). This is true primarily because it is far easier and less costly to meet test objectives by using medium-size machines.

TABLE 1. KEY LARGE WIND TURBINE TESTS BY ELECTRIC UTILITIES  
(Exclusive of Federal R&D Efforts)

Utility	Wind Turbine Description				Date of First Utility Synchronization
	Manufacturer	Rated Power (kW)	Type*	Diameter m(ft)	
Southern California Edison Co.	Bendix	3000	H	50 (164)	Dec. 1981
	ALCOA	500	V	25 (82)	March 1981
Pacific Power and Light Co.	WTG Energy Systems	200	H	24.4 (80)	February 1981
Eugene Water and Electric Board (Oregon)	ALCOA	500	V	25 (82)	January 1981
Hydro-Quebec (Canada)	DAF-Indal Ltd. (Canada)	230	V	24.4 (80)	~April 1977
Pacific Gas & Electric Co.	Boeing Engineering and Construction	2500	H	91.5(300)	~December 1981
Nova Scotia Power Co.	WTG Energy Systems	200	H	24.4 (80)	March 1981
U.S. Bureau of Reclamation/ Colorado River Storage Project	Hamilton Standard	4000	H	77.7(255)	~January 1982
	Boeing Engineering & Construction	2500	H	91.5(300)	~December 1981
ELSAM (WT's at Nibe, Denmark)	Many (Unit A)	630	H	40 (131)	January 1980
	Many (Unit B)	630	H	40 (131)	August 1980

\* H=Horizontal-Axis Wind Turbine; V=Vertical-Axis Wind Turbine

#### Tests in the United States

Many of those U.S. electric utilities that have good wind resources and are aggressively pursuing wind energy programs are testing, or planning to test, megawatt-scale WT's (i.e., Rated  $\geq 1,000$  kW). The most noteworthy examples are two large investor-owned utilities; the Southern California Edison Company (SCE), which is conducting tests at the San Geronio Pass area of California (near Palm Springs) [1,2], and the Pacific Gas and Electric Company (PG&E), which is planning tests for the Solano County area approximately 60 km (40 miles) northeast of San Francisco.

The SCE test involves a unique three-bladed, 3-MW HAWT manufactured by the Bendix Corporation [7], and one of two three-bladed 500-kW Darrieus VAWT's commercially installed by the ALCOA Company [8]. In addition, the U.S. Bureau of Reclamation (a division of the Department of the Interior) is planning to test two megawatt-scale WT's in conjunction with the Colorado River Storage Project's hydroelectric facilities. This project will include a 4-MW Hamilton Standard WTS-4 machine [10] developed by the manufacturer primarily with its own funds. Hamilton Standard was supported by the Swedish Government in a similar 3-MW WT development program. In addition, the Bureau of Reclamation plans to install a commercial version of the MOD-2 WT; three such units have already been installed and are undergoing tests near Goldendale, Washington [11].

The Bureau of Reclamation project, although funded by the Federal Government, is discussed in this paper in conjunction with other electric utilities because the machines are being purchased on fixed-price, non-R&D contracts under the assumption that they have been fully developed and will require no further research and development.



The Bureau of Reclamation WT's will be tested under an interagency agreement between Reclamation and NASA, signed in May 1979. The agreement calls for the design, fabrication, installation, checkout, and operation of megawatt-size wind turbines. All funding for this project is being provided by the U.S. Department of the Interior, Bureau of Reclamation. NASA Lewis Research Center (LeRC) is responsible for project management from the design stage through initial operation.

After Reclamation has accepted the WT's from the contractor, it will operate and maintain the wind turbines, with support from the LeRC, for two years.

Two noteworthy tests using 200-kW WT's built by WTG Energy Systems are being carried out by the Pacific Power and Light Company (PP&L) of Portland, Oregon, and the Nova Scotia Power Corporation (NSP) of Halifax, Nova Scotia. The primary objective of each utility in conducting these tests is to obtain "hands-on" experience with WT's, and to determine whether any adverse interactions occur between the WT and the network. Because of the good wind resources in its service area, PP&L feels that a considerable number of WT's may eventually be installed by private installers, and thus they need early experience with wind machines to be prepared. NSP is also anxious to look at blade dynamic loads to gain an understanding of the correlation between these loads and blade life. To this end, NSP had WTG Energy Systems, Inc., install a limited number of strain-gage sensors on the blades.

The Eugene Water and Electric Board (EWEB), as part of the Central Lincoln Public Utility District in the Oregon/Washington area, has had the ALCOA Company install the only other commercially available 500-kW VAWT. At the present time, EWEB has not purchased the machine; it is awaiting satisfactory completion of acceptance tests by ALCOA. Like PP&L, the major reason for the WT installation is to allow EWEB to obtain "hands-on" experience with all aspects of the installation and evaluate network impacts of the machine. EWEB may go ahead with a more comprehensive test program in the future, but it has yet to formulate firm plans.

#### Canadian WT Programs

The Canadian large WT program, thus far, has concentrated on VAWT technology development and associated tests. Funding for the Canadian Government program has been provided by the National Research Council (NRC), with joint private industry funding provided by Hydro-Quebec, the provincial power authority in Quebec Province.

As shown in Table 1, the major Canadian large WT tests to date have been carried out on a two-bladed, 230-kW VAWT installed on the Magdalen Islands in the Gulf of St. Lawrence [12]. This machine has been used primarily as a research tool to obtain basic engineering data on the aerodynamic, mechanical, and electrical performance of a VAWT. As such, it has not seen a considerable amount of operating time. In the future, after most of the engineering data have been compiled, Hydro-Quebec plans to put the machine in an automatic operation mode to obtain long-term performance as well as operation and maintenance (O&M) data.

## Danish WT Program

Over the past 40 years, approximately 20 large WT's have been installed and operated for extended periods in Denmark. Most of these machines were direct current (DC) versions installed in the 1940's before a full alternating current (AC) network had been installed in Denmark.

At the present time, the Danish Government is working jointly with ELSAM, the electric utility on the island of Jutland in NW Denmark, to test 2 three-bladed, upwind 630-kW machines in the town of Nibe [13]. Development and test activities associated with these machines represent the major large WT activity in Denmark [6]. As indicated in Table 1, the two machines (Nibe A & B) have the same size and power ratings. The major difference between the machines lies in their rotor design. The Nibe A machine employs fixed-pitch blades during operation (with tip flaps for shutdown, etc.) and supports the inner portion of each blade with in-plane and fore-and-aft stays. The Nibe B WT design includes fully pitchable blades (like most U.S. two-bladed large WT's) and supports their full bending moment.

These machines, installed approximately 200 meters (660 ft) from each other, will be comprehensively tested to verify both their engineering designs and mathematical models as well as to check for blade dynamics, sound, wake effects, cluster-coincident output, and site-specific issues such as environmental problems.

## UTILITY INTERCONNECTIONS

The WT tests identified in Table 1 will be conducted with some machines tied strongly to a major transmission network, while others will be installed on distribution systems. Based on the relatively low level of power that is expected to be generated by each WT installation, no network problems are anticipated. Two examples of WT/utility interconnections are provided below.

Figure 1 shows how the two large WT's (up to 3.5 MW of power) will be strongly interconnected with the SCE transmission network. The one-line diagram shows that the output voltages from the two machines are different, but each will be stepped-up by transformers to a common 12-kV level and eventually to a 230-kV level for tie-in to the Devers substation approximately 600 meters (2000 ft) away. SCE is in the process of installing a 500-kV transmission line that will also tie in to the Devers substation. With this future expansion, SCE feels that additional WT capacity could easily be accommodated with no problems expected. The SCE installation is one of the strongest WT interconnections being tested thus far, and is not expected to lead to any adverse network interactions.

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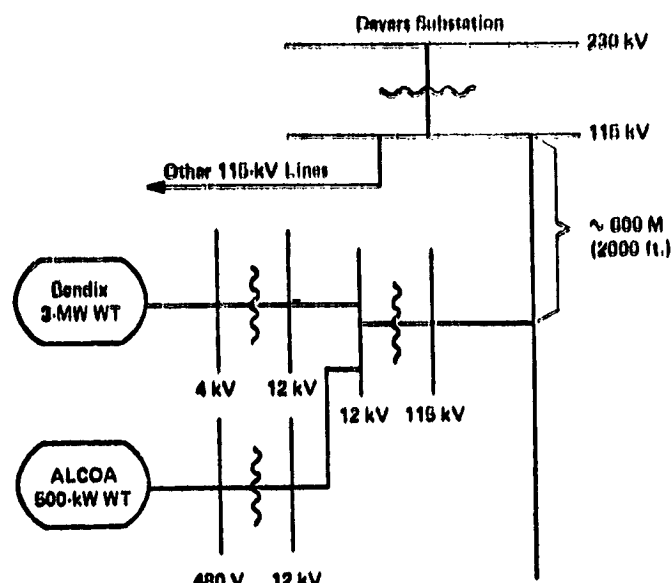


FIGURE 1. ONE-LINE DIAGRAM OF SOUTHERN CALIFORNIA EDISON  
WIND TURBINE INTERCONNECTIONS

Figure 2 is a pictorial representation of the 200-kW WTG Energy Systems, Inc., installation at Wreck Cove, Nova Scotia. The machine will provide power to the 25-kV distribution system which powers a 50-hp water pump close to the WT. The pump is used by NSP to manage the water source between two lakes; its waters ultimately help to serve two 100-MW hydro units. The NSP installation will be tied in to the distribution lines approximately 7 km (4 miles) from the 200 megawatts of hydropower. The 25-kV line serves very few loads in the region of the WT, except the pumps and a logging camp. No network problems are expected at present. In the future, NSP plans to install a new 3.5-MW low-head hydro unit 2.4 km (1.5 miles) from the WT and add power to the distribution system. The firm does not plan to vary the size of the distribution line, and anticipates no problems. This WT/utility interconnection although weaker than that at the SCE test site, is still not expected to pose a problem for the machine size being tested.

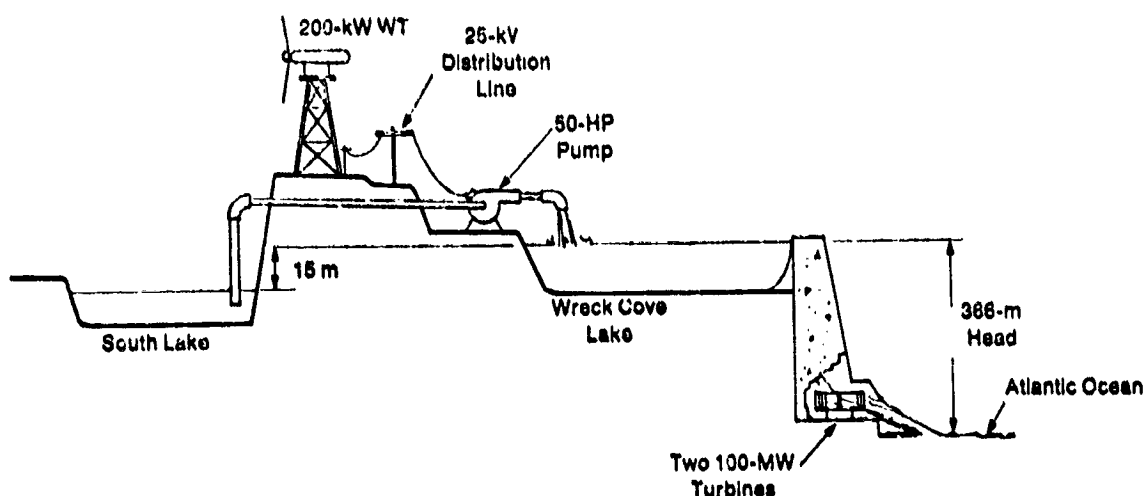


FIGURE 2. WTG ENERGY SYSTEMS, INC./NOVA SCOTIA POWER CO. INSTALLATION  
(WRECK COVE, N.S.)

# INSTRUMENTATION SUMMARY

The amount of instrumentation and the degree of sophistication in the data recording systems vary widely from one utility to the other. Those utilities that are embarking on WT installations as a major research project and have good wind resources in their region have invested considerable time and money to lay the foundation for a thorough understanding of the major technical, environmental, legal, and social issues surrounding WT installations. Other utilities are examining wind energy more superficially along with many other energy options. In this case, a more limited investment is being made and a more scaled-down data system is being installed.

Table 2 provides a synopsis of the instrumentation systems being employed in some of the key electric utility tests discussed. It should be noted that, in the SCE tests, the utility is planning to examine the output of approximately 22 sensors (including those for wind speed and direction at heights of 9.1 meters (30 ft) and 46 meters (150 ft)), while the manufacturers are also adding numerous sensors and recording data for detailed engineering analysis. Many of the manufacturers are also investing time and energy in instrumentation for these early models, because they are essentially engineering prototypes which will provide the basic data by which mathematical models and economic calculations will be verified.

TABLE 2. SUMMARY OF TEST INSTRUMENTATION AT  
KEY ELECTRIC UTILITY LARGE WIND TURBINE TEST SITES

Utility	Number of Sensors	Data Logging		Data Sampling Rates
		System	Format	
Southern California Edison Co.	22*	Data Logger Spectrum Analyzer Oscilloscope	Mag Tape Print/Plot Strip Charts	Every 15 minutes Periodic Periodic
Pacific Power & Light Co.	8	Handwritten	Log Sheet	Weekly
Hydro Quebec (Canada)	25	Oscilloscope FM Recorder Minicomputer	Strip Charts Mag Tape Mag Tape	Periodic Periodic Not Available
Nova Scotia Power Co.	10	Microprocessor	Teletype	Every Hour
ELSAM (Denmark) (As of April 1981)	65	Minicomputer Recorder	Disc, Tape, Plot Strip Chart	5/sec Periodic

\* Other WT mechanical sensors added by manufacturers

## Sensors

All utility experiments will include integrated or instantaneous measurements of the following parameters:

- Power,
- Reactive power,

- Wind speed,
- Wind direction.

Some utilities will measure voltage, output current, power factor, generator speed, barometric pressure, and wet and dry bulb temperatures. In general, the U.S. electric utilities identified in Table 2 do not plan to measure detailed engineering data from the machine, such as torques, bending moments, temperatures, and vibration levels. Measurements of these parameters are being made by the manufacturers to verify their designs.

The WT development programs being conducted in Canada and Denmark include many sensors and comprehensive data recording schemes. These programs are being conducted jointly by the government and the host utility. The programs are aimed at accumulating both engineering data in the early test phases and long-term performance and O&M data later. Measurements of these parameters are being made by the manufacturers to verify their designs. Each project includes sensors to measure the above utility-oriented parameters plus strain gages and accelerometers to measure loads and vibrations.

#### Data Recorders

As shown in Table 2, the level of sophistication in data recording varies greatly from one utility to another. The following six types of data recording schemes have been employed with various test objectives in mind:

Oscillograph Recorder. High-speed oscillograph recorders are periodically employed to test the WT or network transient response to specific phenomena, such as wind gusts, utility tie-in to the network, WT cut-out from the network, and emergency shutdowns. The oscillograph can provide an accurate strip chart trace of key parameters--as long as the basic sensor and recorder responses are sufficient (i.e., adequate bandwidth) to capture the phenomenon of interest. Most oscillographs have a bandwidth of approximately 1 kHz, so the recorder is expected to capture most transient phenomena of interest to electric utilities.

Spectrum Analyzer. A spectrum analyzer can be employed periodically to measure the frequency content inherent in a transient phenomenon. Many of the phenomena analyzed are the same ones which will be portrayed by an oscillograph trace.

Data Logger or Minicomputer. A data logger is usually a low-speed digital sampling system that records the averages of key parameters over periods of 10 to 15 minutes. Generally, the parameters include average wind speed, energy produced, and reactive power consumed or delivered. In some cases, data loggers may use a microprocessor to carry out routine arithmetic operations before recording the data. Data loggers usually record the data on a magnetic tape or disc format. In many cases, a minicomputer that may perform control functions or complex computations can also be used as a data logger by outputting variables to a tape or disc recorder.

FM Recorder. The Canadian large WT test effort is employing a seven-track FM analog recorder to monitor the key variables for short intervals in a given test. The bandwidth of this type of data recording system varies with the speed of the tape recorder drive, but in all cases it should be adequate to monitor WT transient phenomena. If FM-recorded data have to be handled on a computer, they must first be filtered and then subjected to an analog-to-digital (A-to-D) conversion operation before being rewritten on computer-compatible tape.

Strip Chart Recorder. One- to eight-channel analog strip chart recorders of various types have been used in monitoring large WT performance. These recorders may be used to monitor higher speed phenomena (up to approximately 100-Hz bandwidth) or provide long-term monitoring of such parameters as wind speed, instantaneous power, or even blade loads. The benefit in using strip chart records is that test data are immediately available without further processing. They lend themselves well to limited visual examination of data, but are too cumbersome for use in the analysis of many records.

Hand-written Records. Periodically, hand-written records are used where no electronic outputs and no automatic data loggers are available. The written records are usually derived by reading elapsed meters, such as those that record elapsed operating time or cumulative energy generated. The data recorded are usually summary in nature.

## RESULTS TO DATE

Table 3 provides a brief summary of the current status of the major large WT tests carried out by electric utilities in the United States, Canada, and Denmark. In addition Table 1 shows that, except for the Canadian VAWT program which began in 1977, all of the test machines began, or will begin, operation in the 1980 to 1982 time period. Many of these machines have been undergoing installation and checkout during the past year. This section provides a brief summary of the progress on each of the tests.

### Southern California Edison Company (SCE) Tests

Bendix WT Tests. As shown in Table 3, the Bendix machine has operated very little over the past seven months, because SCE is being especially cautious in its test engineering approach [2]. The prototype machine employs many unique design features such as a variable-speed rotor, an hydraulically driven synchronous generator, and a tower which can be rotated to orient the machine into the wind. These features have never before been included in the design of a machine of such a size, and thus SCE is being very careful that no major or unmanageable problems arise because of its test approach.

At the beginning of the test phase, delays were experienced because of light winds. Further delays occurred later because of minor failures in the generator and its exciter circuit. During the early tests SCE installed a conventional automatic synchronizer, thus modifying its initial approach to controlling the machine's speed prior to coming on-line. Recently hydraulic leaks and problems with the data logger have

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caused minor delays. However, tests are proceeding, with a maximum power output of 960 kW measured thus far during approximately 15 hours of total synchronous operation.

**TABLE 3. STATUS OF KEY LARGE WIND TURBINE TESTS  
BY ELECTRIC UTILITIES  
(Exclusive of Federal R&D Efforts)**

Utility	Wind Turbine	Status	Hours of Operation	Maximum Power Produced (kW)	Energy Generated (MWh)
Southern California Edison Co.	Bendix (3000 kW)	Support Engineering Tests	~15	960	>2
	ALCOA (500 kW)	Reassembly Following Failure	N.A.	>500	N.A.
Pacific Power & Light Co.	WTG Energy Systems (kW 200)	Automatic Operation	~500	~400	N.A.
Eugene Water and Electric Board (Oregon)	ALCOA (500 kW)	Operation Ceased Awaiting Changes	N.A.	N.A.	N.A.
Hydro Quebec (Canada)	DAF-Indal (230 kW)	Support Engineering Tests	~300	~200	N.A.
Pacific Gas & Electric Co.	Boeing Mod-2 (2500 kW)	Site Work	-	-	-
Nova Scotia Power Co.	WTG Energy Systems (200 kW)	Awaiting Partial Redesign	12	N.A.	N.A.
U.S. Bureau of Reclamation/ Colorado River Storage Project	Hamilton-Standard (4000 kW)	Site Work	-	-	-
	Boeing Mod-2 (2500 kW)	Site Work	-	-	-
ELSAM (Denmark) (as of April 1981)	Nibe A (630 kW)	Rework Following "1000 hr" Inspection	845	~650	152
	Nibe B (630 kW)	Automatic Operation	453	~800	53

N.A. indicates data not available

**ALCOA WT Tests.** The first synchronous operation of the ALCOA 500-kW VAWT at the SCE site occurred early in March 1981. The machine operated for a few hours (less than 10) before it was partially destroyed during checkout tests on April 3, 1981. The machine was damaged when an overspeed condition occurred that resulted from a complex series of events. The machine reached a rotational speed of 60 rpm before destruction; its normal design speed is 41 rpm. The whole series of events leading up to the failure occurred in 39 seconds. The main reasons for the failure, according to the manufacturer, included:

- An omission in the WT's computer control program that was to bring the WT to a safe stop with its service brake at the proper time.
- A sudden line voltage drop of 25 percent which occurred when the WT generator came on-line; the drop was caused by excessive transformer impedance. The voltage drop also caused the WT controller to malfunction temporarily.

- The aerodynamic efficiency of the Darrieus rotor being higher than ALCOA models had predicted. The ALCOA machine components (viz., the brakes, attachments, and such) were not built strong enough to withstand the higher loads.

#### Pacific Power and Light Company (PP&L) Tests

At the present time, the PP&L tests of the 200-kW HAWT built by WTG Energy Systems, Inc. (WTG) are proceeding in a relatively smooth manner. The machine began automatic operation in June 1981. Prior to this, the WT was not operated for a short period while a problem was being addressed. WTG had identified a design problem in which transient wind gusts were generating excessively high transient output-power fluctuations. WTG was initially concerned that the associated fluctuating system torques might be damaging to the system.

In June 1981, PP&L and WTG agreed to begin testing the WT in an automatic test mode. In the meantime, WTG is exploring the possibility of attenuating the rotor torque variations caused by wind gusts by installing an induction generator instead of the present synchronous unit.

#### Eugene Water and Electric Board (EWEB) Tests

The ALCOA 500-kW VAWT, installed at an Agate Beach site within the EWEB district, operated for a very few hours before it was shut down. EWEB is awaiting word on a fix to the problem that arose on the similar unit that was installed at the SCE test site. Present plans indicate that the machine design will be modified in the fall of 1981 to include a new gear box. At the same time a lower rotor rpm (approximately 36 rpm) will also be employed. The machine is expected to be operational early in 1981.

#### Hydro-Quebec Tests

The DAF-Indal, Ltd., 230-kW VAWT installed in the Magdalen Islands has been operated periodically in support of engineering tests. It has only operated approximately 100 hours since being repaired early in 1980--following a failure in 1978, and has not as yet achieved its full output power of 230 kW. Much of the detailed test data from the machine has not yet been evaluated by the National Research Council of Canada, because of manpower and funding limitations.



### Pacific Gas and Electric Company (PG&E) Tests

The PG&E MOD-2 2,500-kW WT is expected to be installed at the Solano County, California, site in the fall of 1981, and tests on the WT are expected to commence in early 1982, following the successful completion of acceptance tests. PG&E has plans for a comprehensive data acquisition system, as well as plans for detailed engineering, sound, television interference, and environmental tests.

### U.S. Bureau of Reclamation Tests

Hamilton Standard WT Tests. The first 4-MW WT (Model WTS-4) to be built by Hamilton Standard experienced a few minor schedule delays, but in general is proceeding toward first rotation early in 1982 [10]. Fiberglass blades for the machine are being fabricated at Hamilton Standard's unique blade-winding facility in East Granby, Connecticut. Many of the early prototype engineering problems that might be experienced on this first unit are expected to be addressed in the similar 3-MW machine (Model WTS-3) being built for the Swedish Government for delivery late in 1981.

Boeing MOD-2 WT Tests. Many of the parts for the MOD-2 WT were ordered by Boeing in 1979-1980 as part of the DOE-funded cluster tests that ultimately led to the installation of three MOD-2 WT's at a site near Goldendale, Washington. Early in the DOE program, it was tentatively planned that a fourth MOD-2 WT would be installed and tested. Therefore, many of the parts were available for the Bureau of Reclamation installation. Their availability resulted in very rapid progress on the machine installation. The only design change on the MOD-2 WT was to double the strength of the yaw drive system in order to accommodate loads at the higher cut-out wind speed of 26.8 m/s (60 mph). At the present time, it appears that the machine will undergo its first network synchronization in the early-to-mid-fall 1981 period.

### ELSAM WT Tests

The Nibe A & B WT's have been subjected to an arduous series of tests from the time of their initial installation until their full automatic operation approximately one year later. The tests are being carried out by ELSAM, the Danish electric utility for Gotland in northwest Denmark. During this period, personnel from both ELSAM and the Risø National Laboratory in Denmark conducted an exhaustive series of startup, shutdown, safety system, and engineering tests to determine whether the machine would perform at an acceptable level. Numerous technical problems were overcome during this period, the primary ones being associated with the control computers and the hydraulic systems. During the tests in which the machines were providing power to the 20-kV ELSAM network, no voltage or frequency problems were identified.

The summary performance data for each machine, as shown in Table 3, are current as of April 1, 1981. The following is a brief account of the results of tests conducted during the past year.

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Nibe A WT. The Nibe A WT went into automatic operation in August 1980, and by November 1980 it had run for 845 hours. At that time it underwent a "1000-hour" inspection, which revealed a number of small problems; e.g., oil leaks, corrosion, and bearing deterioration. However, the major finding was that many welds in key, highly stressed locations had been improperly made. Many of these welds were made in the area of the blade stays. However, the machine has undergone a major rework on the key welded joints and should be back in service in July 1981.

Nibe B WT. The Nibe B WT, which employs three fully pitchable blades, has been operating satisfactorily since it began full automatic operation in February 1981. Since then, it has logged 453 hours of operating time, and no major problems have been identified thus far.

## OTHER WIND ENERGY VENTURES

There are two other major types of wind energy ventures that could lead to substantial new wind energy installations in utility systems. These include (1) DOE-funded R&D programs, and (2) private wind energy installations funded by independent investors.

The major DOE-funded R&D effort at the present time is the 7.5-MW MOD-2 WT cluster at Goldendale, Washington [11] which came on line late in 1980 and early 1981. Comprehensive and practical WT performance, dynamic, and operational data are expected to be completed at that test site. Table 4 provides a brief description of the installation and also identifies the other major private ventures being undertaken in the United States.

TABLE 4. OTHER MAJOR WIND TURBINE CLUSTER TESTS  
IN CONJUNCTION WITH ELECTRIC UTILITIES

Project Developer	Utility	Wind Turbine	Number of Wind Turbines	Installed Capacity (MW)	Date of Expected Completion
U.S. Department of Energy	Bonneville Power Administration	Boeing Mod-2 (2.5 MW)	3	7.5	May 1981 (Operational)
Windfarms Ltd.	Hawaiian Electric Co.	Hamilton Standard WTS-4 (4 MW)	20	80	~ 1985
U.S. Windpower, Inc.	Public Service Company of New Hampshire	U.S. Windpower (30 kW)	20	0.6	December 1980 (Operational)
Windfarms, Ltd.	Pacific Gas and Electric Co.	N.A.	146	350	~ 1985-90

N.A. indicates data not available

Because of the favorable tax credits that are permitted to private wind energy ventures, and the appealing legal environment provided by the Public Utilities Regulatory Policy Act (PURPA) of 1978, many private companies have been created. Their objective is to install WT's and then sell the electricity they generate back to the utilities. These

companies, backed by funds provided by investors, have often been referred to as "windfarmers," because the WT configurations planned in these ventures often take the form of clusters or "farms" of many machines. The output of these clusters will be fed directly into the transmission and distribution networks of the local electric utility. People in the industry expect that the ownership of some WT clusters may eventually be acquired by local utilities after the clusters have exhausted most of their tax advantages to the investor.

The three major investor-funded WT ventures in the United States are briefly summarized in Table 4. The only private venture that is currently operating is the U.S. Windpower 600-kW cluster located on Crotched Mountain in southern New Hampshire. No formal test results are publicly available on that project. The two Windfarms Ltd. projects identified in Table 4 are in various stages of planning, negotiation, and design--with full operation expected by the mid-1980's, when the present advantages of the federal energy tax credit are scheduled to expire.

#### SUMMARY

At the present time, many electric utilities with good wind resources in their respective regions are proceeding to test pilot WT installations. The overall goal of these early installations is to provide utilities with "hands-on" experience, so that they will be prepared to manage wind energy as a new energy source when it becomes economically attractive. At the same time, many utilities are attempting to develop a technical understanding of WT's so that they can effectively interact with private WT investors and developers who may attempt to sell wind-generated electricity to the utility.

However, no large WT installations have advanced beyond the engineering prototype test stage. In this stage of development many typical hardware and software design problems are being identified and remedied. Therefore, the test results thus far do not alter current projections for attractive wind turbine performance and economics when the technology matures and production machines become available.

#### ACKNOWLEDGEMENT

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## QUESTIONS AND ANSWERS

W. A. Vachon

From: J. Westergaard

Q: For analysis of the operation and maintenance costs over the 20 or 30 year time period, what factors are considered in your life cycle cost models?

A: *Large WT manufacturers have prepared reports identifying the O & M assumptions in their cost-of-energy projections. In my study of O & M experiences on research machines, I have been trying to examine the outage times and associated problems as if they were handled by the local utilities in a timely manner with the assumptions that personnel and spare parts are available.*

From: M. F. Merriam

Q: What do you mean by the remark that WTG-200 for PP&L is a 200 kw machine with a 375 kw generator?

A: *Because the WTG Energy Systems WT employs a stall-regulated rotor (i.e. fixed pitch), the power output from their machine can reach as high as approximately 400 kw at very high wind speeds. WTG has, therefore, installed a 375-kw (nameplate rating) generator to accommodate the higher output, and rates the machine conservatively at 200 kw at approximately a 28 mph wind speed. They could just as easily have called the machine a 300-kw unit, but it would only reach that power output at a much higher wind speed.*

UTILITY EXPERIENCE WITH TWO  
DEMONSTRATION WIND TURBINE GENERATORS

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ABSTRACT

Southern California Edison's interest in wind energy started prior to 1975 and has been spurred by the Company's large proportion of oil-fired generation, an excellent wind resource and the belief that wind would be the first alternate energy source to reach commercialization.

Edison has committed 360 MW of nameplate generating capacity to wind energy by year 1990 in its long-range generation plan. To reach this goal the Company's wind energy program focuses on three areas: the continuous evaluation of the wind resource, the hands-on demonstration of wind turbine generators (WTG) and an association with wind park developers.

Two demonstration WTGs have been installed and operated at Edison's Wind Energy Center near Palm Springs, California: a 3 MW horizontal axis Bendix/Schachle WTG and a 500 kW vertical axis Alcoa WTG. They are part of a one to two year test program during which the performance of the WTGs will be evaluated, their system operation and environmental impact will be assessed and the design criteria of future WTGs will be identified.

Edison's experience with these two WTGs is summarized and the problems encountered with the operation of the two machines are discussed in this paper. The information needs of a utility planning to use WTGs as a cost-effective and reliable resource are also briefly addressed.

## INTRODUCTION

The demonstration testing of two large WTGs is only one aspect of Southern California Edison's wind energy program. As illustrated in Figure 1, other aspects include a continuing evaluation of the wind resource on Edison's service territory with particular emphasis on the San Geronio Pass region, evaluation of WTG designs proposed by the DOE and others, system integration and economic studies. Recently, the development of cooperative commercial wind projects, an activity not shown in the figure, has become an important part of the program.

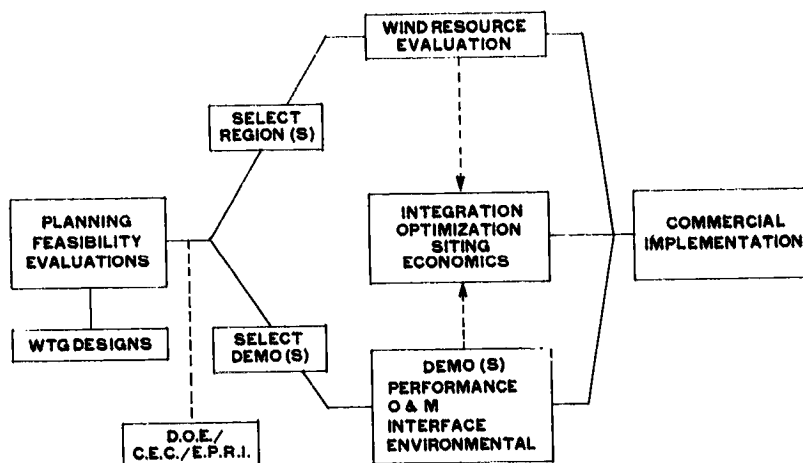


Figure 1: The Edison Wind Energy Program

The evaluation of WTG designs and systems are aimed at determining the technical, economic, socio-economic, land use and environmental factors associated with the installation of multi-unit wind farms.

The evaluation of the wind resource, stated in 1975, has continued with the installation by the DOE of a 150 foot meteorological tower near the Edison Devers Substation, the monitoring of winds in the San Geronio Pass through the installation of 19 monitoring stations as part of a study sponsored by Edison and the California Energy Commission, and the installation of a 330 foot meteorological tower.

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The development of cooperative commercial wind projects was initiated with the preparation of a Wind Park Opportunity Announcement (WPOA). Response by private entrepreneurs and corporations was excellent, leading to promising negotiations. Through the purchase of energy produced by wind parks Edison hopes to meet a significant portion of its wind-generated resource goal.

The demonstration testing of large WTGs originated when Edison identified the Schachle variable rotor rpm WTG concept as a promising design. A joint effort with Bendix Corporation resulted in the installation of a 3 MW horizontal axis machine placed in first operation in December 1980. Edison's interest in alternate concepts included the vertical axis designs and led to the installation in March 1981 of a 500 kW machine designed and fabricated by Alcoa (Figure 2).

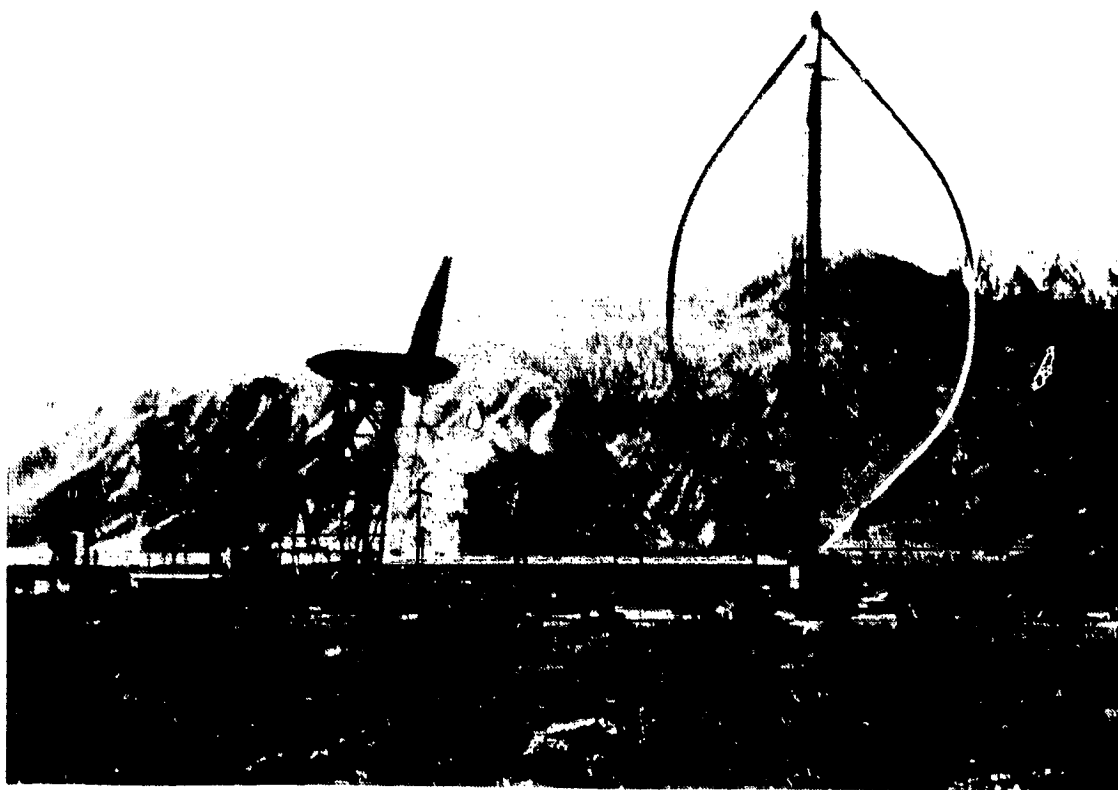


Figure 2: Alcoa and Bendix/Schachle WTGs



## THE EDISON WTG TEST PROGRAM

The test program was designed to provide, over a period of two years, the data needed to support the planning, installation and operation of WTGs on a commercial scale. Although originally developed for the testing of two specific WTG designs, the program was designed to accommodate any wind turbines aimed at the utility market.

The overall scope of the program is to document the performance of the WTGs being tested, to train Edison personnel as WTG operators, to assess the operation and maintenance requirements and to evaluate the system impact of the WTGs. The environmental issues associated with WTGs will also be explored and the design criteria of commercial units will be identified. The key questions to be answered by the program in the areas of performance and system impact are outlined in Tables 1 and 2 respectively.

### WTG PERFORMANCE

- POWER OUTPUT
- ENERGY OUTPUT
- AERODYNAMIC EFFICIENCY ( $C_p$ )
- MECHANICAL EFFICIENCY (POWER TRAIN LOSSES)
- OVERALL EFFICIENCY
- WAKE CHARACTERIZATION (SPACING)

Table 1: Key WTG Performance Questions

## WTG SYSTEM OPERATION IMPACT

- CAPACITY FACTOR
- DYNAMIC RESPONSE TO WIND GUSTS
- POWER FACTOR CONTROL
- VARS CONSUMPTION
- ADEQUACY OF ELECTRICAL PROTECTION DEVICES
- START/STOP IMPACT

Table 2: System Operation Aspects of WTG Operation

The Edison WTG test site is located at the eastern end of the San Geronio Pass, approximately eight miles north of the city of Palm Springs, California. The site is adjacent to Edison's Devers Substation which has a long history of data collection. Partial wind speed and direction records were kept as early as 1962 as part of an effort to solve wind-related problems with distribution lines in the Palm Springs area. In mid-1976 the site was proposed to ERDA as a candidate site for the MOD-OA WTG. The site was later selected by the DOE to be one of the 17 candidate sites in the program and was instrumented with a 150-foot meteorological tower. The location of the tower with respect to the WTGs is shown in Figure 3. The close proximity of the substation to the WTGs afforded a cost effective electrical connection to the Edison grid. Recent data have shown that average wind velocities are in the order of 18 mph at 150 feet. Maximum wind velocities of 90 mph have been recorded.

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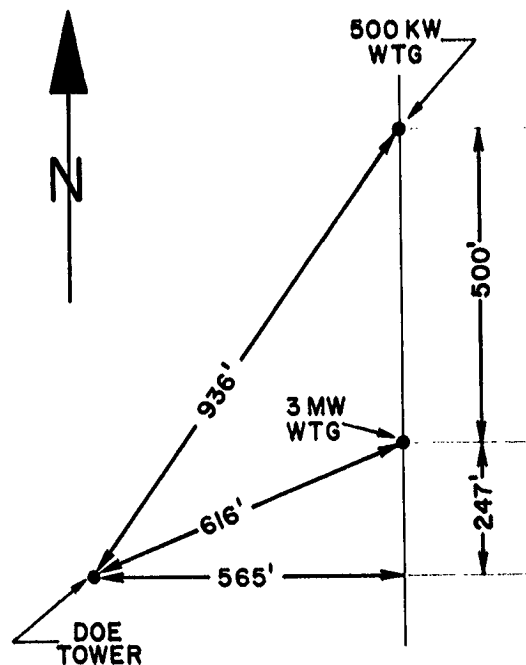


Figure 3: DOE Meteorological Tower Location

Three major sources<sup>\*</sup> of data will be used during the test program: continuous performance, special test and manually logged data. The nature of the data is outlined in Table 3. The data acquisition system illustrated in Figure 4 uses a data logger and a magnetic tape drive to sample and record performance parameters at predetermined time intervals. Computer programs have been developed to process the data and summarize performance statistics under three tabulation formats: daily wind data, daily WTG performance summary and monthly performance analyses. Tables 4, 5 and 6 illustrate these three formats.

#### EDISON'S EXPERIENCE TO DATE

The Bendix/Schachle WTG is a horizontal axis machine with a 165 foot, three-bladed rotor operating at variable speed to control the tip speed versus wind speed ratio.

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**A. CONTINUOUS PERFORMANCE DATA**

- DATA LOGGER
- COMPUTER TABULATIONS

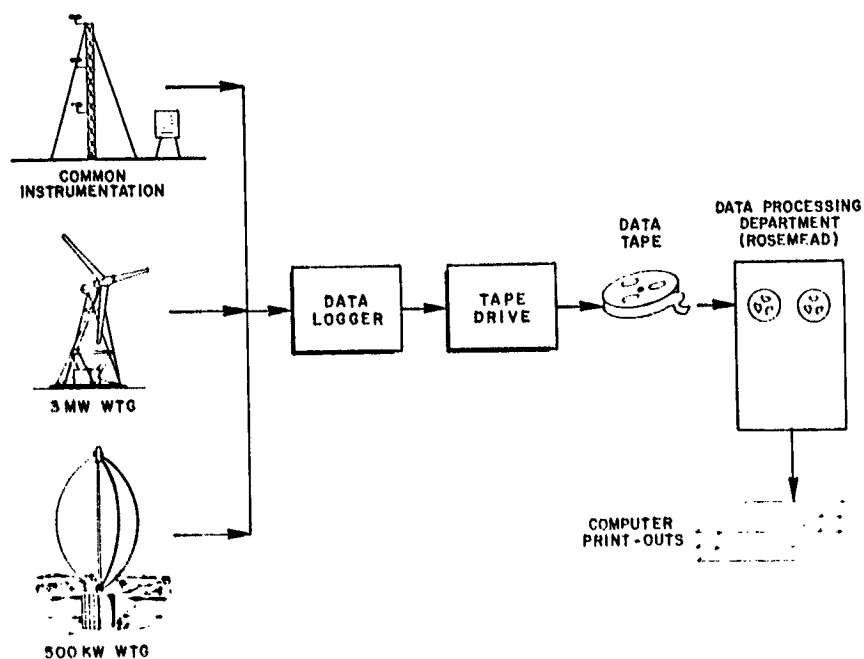
**B. SPECIAL TEST DATA**

- DYNAMIC TESTS
- SOUND DATA
- OTHER

**C. MANUALLY LOGGED DATA**

- STATION LOG
- O&M COSTS
- SHUTDOWN CAUSES

**Table 3: Data Sources for Test Program**



**Figure 4: Edison Data Acquisition System**

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DAILY WIND DATA SUMMARY  
DEVERS WIG TEST SITE  
DATE: 111

HOUR ENDING AT	WIND SPEED AT DOE TOWER MILES PER HOUR			WIND SPEED SHEAR COEFFICIENT	PREVAIL WIND DIRECTION AT 100 FEET	DRY BULB TEMPERATURE DEGREES FAHR.	BAROMETRIC PRESSURE INCHES HG.	POWER AT 100 FEET KW/ SQ FOOT
	30 FEET	200 FEET	150 FEET					
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	PA N	N 1A%	?	AN n	29.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0					9.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
10:00	20.0	24.0	26.0	0.163	2	80.0	29.92	0.068
DAILY AVERAGES	20.0	24.0	26.0	0.163	4	80.0	29.92	0.068

TOTAL ENERGY IN THE WIND FOR THIS DAY -- 1.628 KWH PER SQUARE FOOT  
EQUIVALENT AVERAGE WIND SPEED FOR THE DAY -- 24.0 MILES PER HOUR

**Table 4: Daily Wind Data Summary**

DAILY WTG PERFORMANCE SUMMARY  
3 MEGAWATT BENDIX/ SCHACHLE  
DATE: 111

HOUR ENDING AT	WIND SPEED AT HUB MILES PER HOUR	WIND POWER FOR SHEPT AREA KILOWATTS	ELECTRICAL POWER PRODUCED KILOWATTS	ELECTRICAL POWER ABSORBED KILOWATTS	NET ELECTRICAL POWER KILOWATTS	COEFFICIENT OF PERFORMANCE
10:00	24.4	1594.6	800.0	100.0	700.0	0.4390
10:00	24.4				0.0	0.4390
10:00	24.4		SUBSTITUTE DATA		0.0	0.4390
10:00	24.4				0.0	0.4390
10:00	24.4				0.0	0.4390
10:00	24.4		FOR FORMAT ONLY		0.0	0.4390
10:00	24.4				0.0	0.4390
10:00	24.4	1594.6	800.0	100.0	700.0	0.4390
DAILY AVERAGES	24.4	1594.6	800.0	100.0	700.0	0.4390

### DAILY STATISTICS

ENERGY PRODUCED (KILOWATT-HOURS)	19200.0	NUMBER OF HOURS BETWEEN MACHINE	
ENERGY ABSORBED (KILOWATT-HOURS)	2400.0	CUT-IN AND CUT-OUT SPEEDS	0
NET ENERGY (KILOWATT-HOURS)	16800.0	HOURS OF WIND TURBINE OPERATION	0
NUMBER OF MACHINE STARTS	0	WTG AVAILABILITY (PERCENT)	0.0
NUMBER OF WIND-RELATED SHUTDOWNS	0	WTG CAPACITY FACTOR (PERCENT)	23.3
NUMBER OF NON-WIND-RELATED SHUTDOWNS	0		

### CUMULATIVE STATISTICS TO DATE

ENERGY PRODUCED (KILOWATT-HOURS)	0.	WTG AVAILABILITY (PERCENT)	0.0
HOURS OF MACHINE OPERATION	0	WTG CAPACITY FACTOR (PERCENT)	0.0

**Table 5: Daily WTG Performance Summary**

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MONTHLY WTG PERFORMANCE ANALYSIS  
3 MEGAWATT BENDIX/ SCHACHLE  
DATE : 800101

WIND SPEED AT 100 FEET	NUMBER OF HOURS	CONTROL ANEMOMETER MPH	ROTOR RPM	GENERATOR VOLTS	GENERATOR AMPS	WIND POWER AVAILABLE KILOWATTS	REAL POWER KILOWATTS	REACTIVE POWER KILOWARS	POWER FACTOR	COEFFICIENT OF PERFORMANCE	YAW ERROR DEGREES	BLADE PITCH DEGREES
BELOW CUT-IN	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
34	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
35	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
36	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
37	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
38	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
39	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
40	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
41	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
42	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
43	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
44	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
45	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
46	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
47	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
48	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
49	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
50	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
51	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
52	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
53	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
54	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
55	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
56	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
57	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
58	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
59	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
60	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
ABOVE CUT-OUT	0.0	0.0	0.0	0.	0.0	0.	0.	0.	0.0	0.0	0.0	0.0
AVERAGES/ TOTALS	12.5	17.0	23.0	2000.	100.0	1595.	800.	100.	0.992	0.502	5.0	45.0

SUBSTITUTE DATA

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Table 6: Monthly WTG Performance Analysis

The proprietary blade design and tip speed control are expected to yield high rotor wind energy conversion efficiencies. Fixed displacement pumps and variable displacement motors are used to maintain a constant 1200 rpm generator speed. The WTG nacelle is supported by a 110-foot rotating tower. Electrical power is transmitted from the WTG to the test site substation through slip rings mounted at the base of the tower. The rotor is designed to operate at a constant blade pitch angle up to the rated wind speed. At and above rated wind speed the rotor blades are moved toward their feathered position. A diagram of the power drive train is shown in Figure 5.

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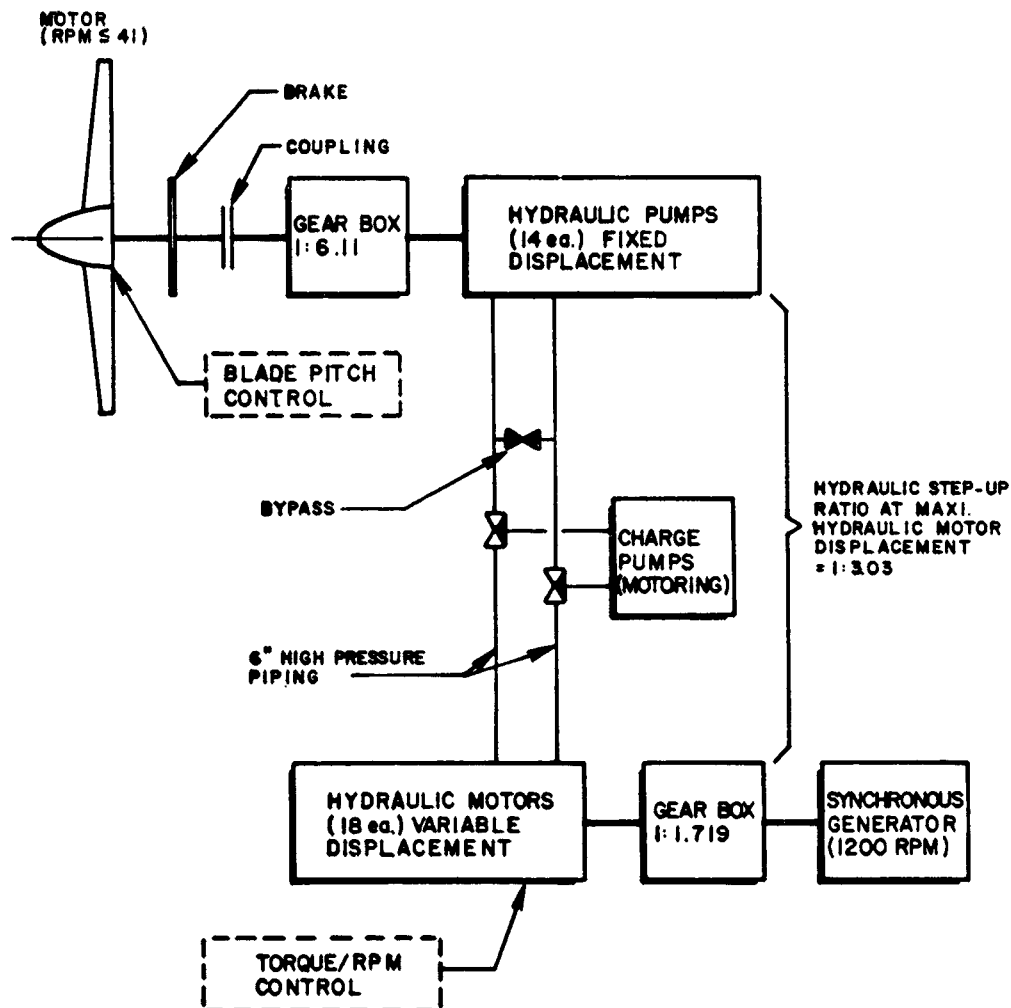


Figure 5: Bendix/Schachle WTG Power Drive Train

The WTG was first operated on-line on December 15, 1980. A gearbox bearing failure and low winds prevented operations until March 3, 1981. The bearing failure was caused by a lack of lubrication traced to the omission of an oil line.

Problems were encountered during synchronization of the generator with the Edison grid. No generator field was applied prior to closing of the main breaker in the original synchronizing method. Recurring diode failures in the exciter led to a change of method and the installation of a synchronizing relay. The generator and grid voltages are now matched prior to the closing of the main breaker by the synchronizing relay.

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The WTG is rated at 3 MW in 40 mph winds at hub height. However, the current operating envelope is limited to lower power and wind speed values to allow for measurement and analysis of blade stresses.

Problems have also been experienced with the Edison data acquisition system mainly related to poor quality control. The computer programs used to process the performance data are being tested as the WTG operating time is building up.

To date, power levels in excess of 1 MW have been reached. Development efforts are currently focused on the implementation of automated controls, the expansion of the operating envelope and the training of operators.

The Alcoa WTG is a vertical axis machine with a 123 foot, three-bladed rotor driving a 500 kW induction generator through a fixed ratio gearbox. The rotor is held by 6 guy cables anchored 165 feet away from the generator enclosure. The aluminum blades have a 29 inch cord and a symmetrical NACA 0015 airfoil. The WTG is started by a 30 hp motor and stopped by a service brake and emergency brake mounted on the generator shaft. A diagram of the power drive train is shown in Figure 6.

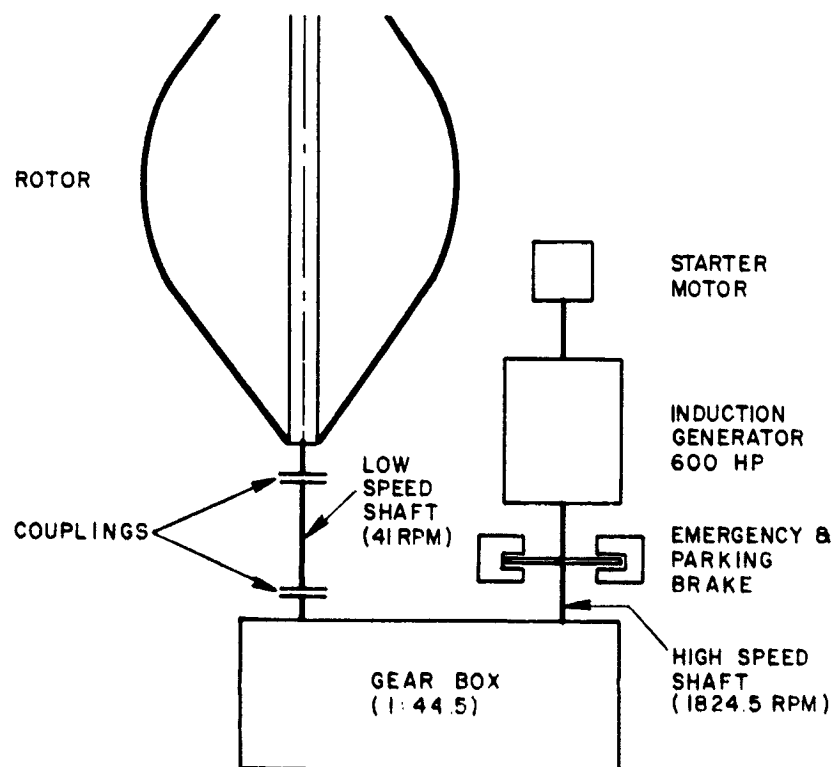


Figure 6: Alcoa WTG Power Drive Train



The WTG was first operated on-line on March 17, 1981 by Alcoa personnel and started preacceptance tests. On April 3, 1981 the rotor failed and was destroyed. The cause of failure was an overspeed condition related to controls software and a malfunction of the brakes. At approximately 60 rpm the blades separated from the torque tube and hit the guy cables. The overspeed was 50% of the 40 rpm normal rotor speed. Test data and analyses have indicated that the aerodynamic performance of the rotor notably exceeded Alcoa's predictions and contributed to the overspeed condition.

Plans are being formulated to rebuild the WTG following testing of a modified WTG installed in Oregon. The new WTG will be extensively redesigned.

#### UTILITY PLANNING NEEDS

A general concern expressed by the utilities when they investigate WTGs as a generation resource relates to the lack of operating data. Although this situation is rapidly changing, the need for accurate information will remain during the coming years. Assistance to utilities from the wind power community should be focused on providing information on reliability, O&M costs, operating constraints and system interface requirements. Performance guarantees and field support will be deciding factors in the selection of WTG. Acceptance criteria also need to be developed and consistent methods for predicting energy production need to be agreed upon. Given the wind regimes of their selected sites, the utilities need to be in a position to assess the energy costs of WTGs with a good level of confidence.

The key to obtaining their information will be the continuation of existing, and the creation of new WTG demonstration programs designed to generate the appropriate actual operating data while providing the necessary utility experience.

## QUESTIONS AND ANSWERS

M. C. Wehrey

From: F. R. Goodman, Jr.

Q: How was the existing spacing of the two test wind turbines determined?

A: *Due to the prevailing westerly wind direction at the test site and the north-south alignment of the wind turbines, approximately 6 rotor diameters of the vertical axis machine (or 500 feet) were deemed adequate spacing distance.*

From: Anonymous

Q: How much penetration does 360 Mw represent?

A: *360 Mw of rated wind resources would represent approximately 120 Mw of firm capacity or from .5 to 1% of the total projected SCE system firm capacity in 1990.*

**N83 19267**

WTS-4 SYSTEM VERIFICATION UNIT FOR  
WIND/HYDROELECTRIC INTEGRATION STUDY

A. W. Watts, PE  
Bureau of Reclamation  
Lower Missouri Region  
P.O. Box 25247  
Denver, Colorado 80225

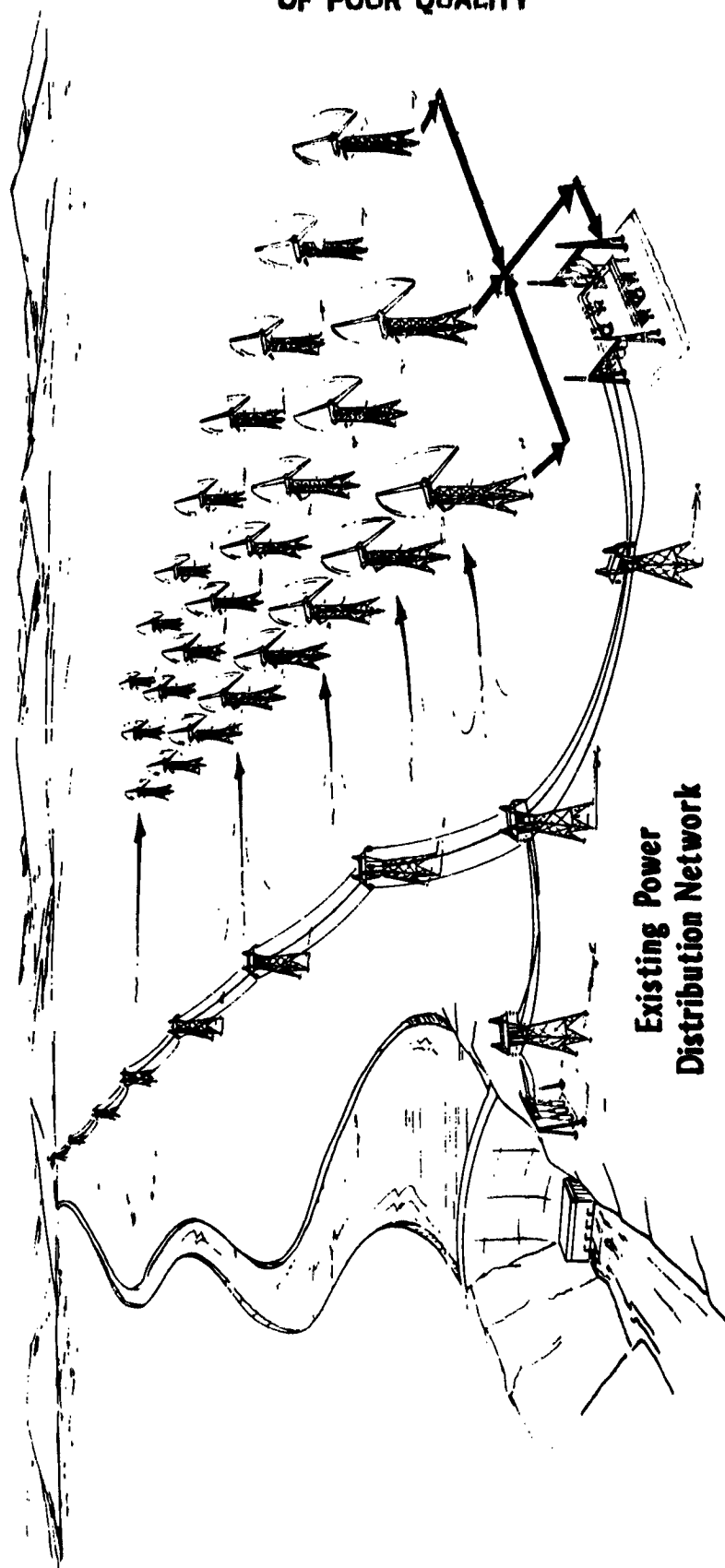
## ABSTRACT

The Bureau of Reclamation (Reclamation) initiated a study to investigate the concept of integrating 100 MW of wind energy from megawatt-size wind turbines with the Federal hydroelectric system. As a part of the study, one large wind turbine was purchased through the competitive bid process and is now being installed to serve as a system verification unit (SVU). Reclamation negotiated an agreement with NASA to provide technical management of the project for the design, fabrication, installation, testing, and initial operation. Hamilton Standard was awarded a contract to furnish and install its WTS-4 wind turbine rated at 4 MW at a site near Medicine Bow, Wyoming. The purposes for installing the SVU are to fully evaluate the wind/hydro integration concept, make technical evaluation of the hardware design, train personnel in the technology, evaluate operation and maintenance aspects, and evaluate associated environmental impacts. The SVU will be operational in June 1982. Data from the WTS-4 and from a second SVU, Boeing's MOD-2, will be used to prepare a final design for a 100-MW wind farm if Congress authorizes the project.

## WIND/HYDROELECTRIC INTEGRATION STUDY

The Bureau of Reclamation (Reclamation) has under construction two megawatt-size wind turbines at its Medicine Bow, Wyoming, site to serve as system verification units (SVU). One unit is the Hamilton Standard 4-MW unit designated as WTS-4. The second unit is the Boeing 2.5-MW unit designated as the MOD-2. Reclamation engineers, late in 1976, developed a concept for integrating large quantities of wind energy with the Federal hydrosystem for a wholesale power supply, see Figure 1. A 3½-year feasibility study of this concept, based on an installation of 100 MW, was completed in June 1981. The study and the installation of two SVU's were designed to accomplish the following objectives:

# **INTEGRATION OF WIND AND HYDROELECTRIC POWER**



**Wind Turbine Array  
Medicine Bow, Wyoming**

**Existing Power  
Distribution Network**

**Existing Colorado River  
Storage Project**

Wind/Hydro Integration Concept  
Figure No. 1

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1. Measure and evaluate the wind resource in the Medicine Bow area;
2. Test the concept of integrating wind and hydroelectric generation facilities for production of wholesale power;
3. Determine the environmental impacts of wind generation within the study area;
4. Evaluate the feasibility and justification for constructing a large-scale wind farm;
5. Measure the acceptance and reaction of the public to the plan, and
6. Train personnel in the technology.

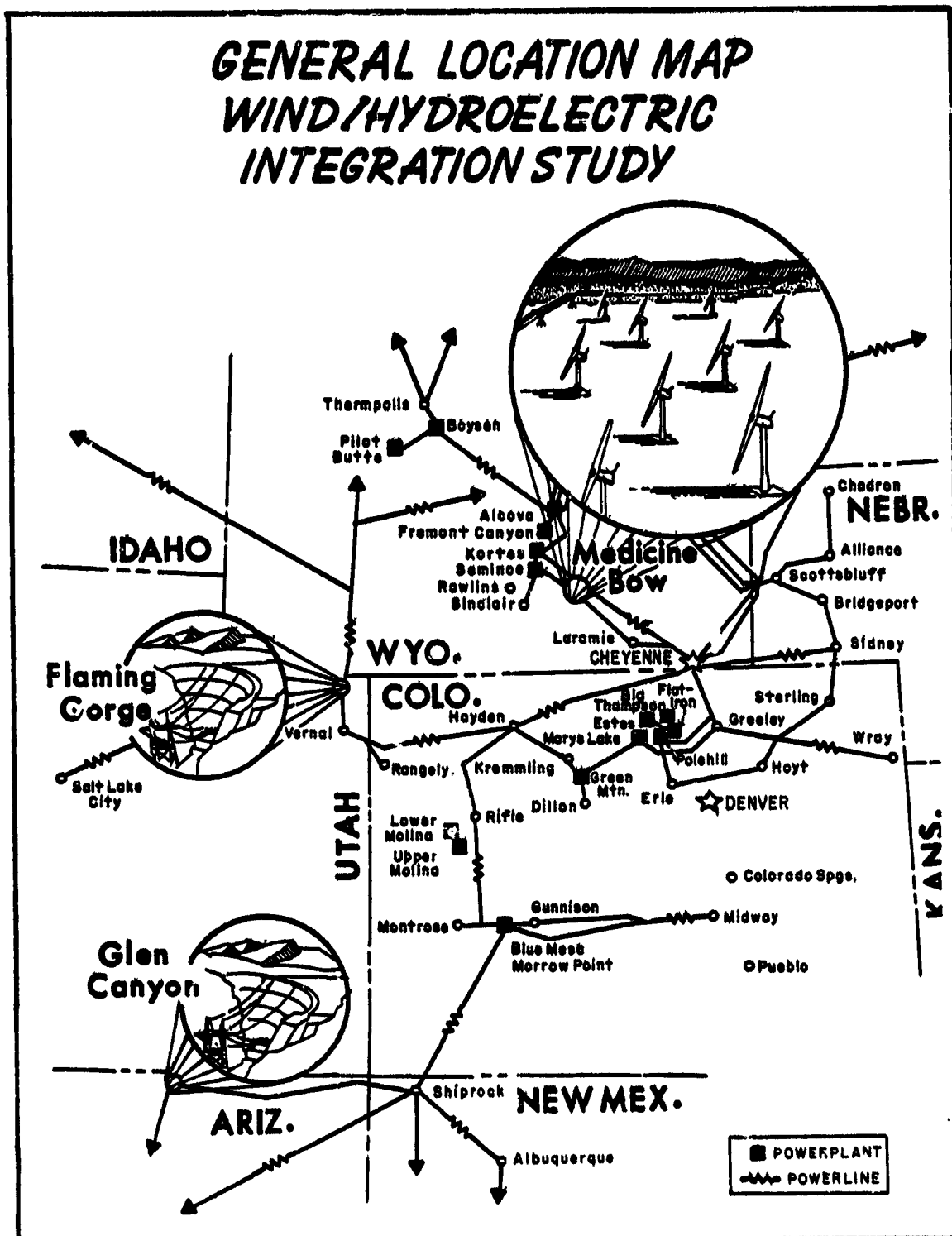
Since the use of multiple large wind turbines at a site for central station-type power supply is a new technology and there is no precedent for validating data for the study, it was determined early in the study that one or more SVU's operating at the site were needed before a definite plan report could be prepared for the 100-MW wind farm.

The wind resource is in an area in south-central Wyoming near the town of Medicine Bow. The hydroelectric system is the Colorado River Storage Project (CRSP). This relationship is shown in Figure 2. The characteristics of these two resources offer a good opportunity to determine the feasibility of integrating a large amount of energy from the nonfirm energy supply produced by large wind turbines with the firming capability and energy storage in reservoirs provided by the existing hydrosystem to produce a large block of wholesale electric power. The two largest hydro developments are shown, Glen Canyon and Flaming Gorge.

There are 22 other existing hydroelectric plants in the Federal system associated with the study.

The wind resource selected for this study is a large land area near Medicine Bow, Wyoming, shown in Figure 3. The location is a high, arid plateau area about 2.133 km (7,000 feet) and is located near existing Federal transmission lines and has a high average annual wind potential. A major factor of the wind/hydroelectric integration concept is to locate the wind turbines at the best possible wind resource site in the same manner that hydrodams are located at the best hydro-site. The wind turbines can be a great distance from the hydro-generation as long as the transmission system has the capacity to serve the loads from the various generating locations.

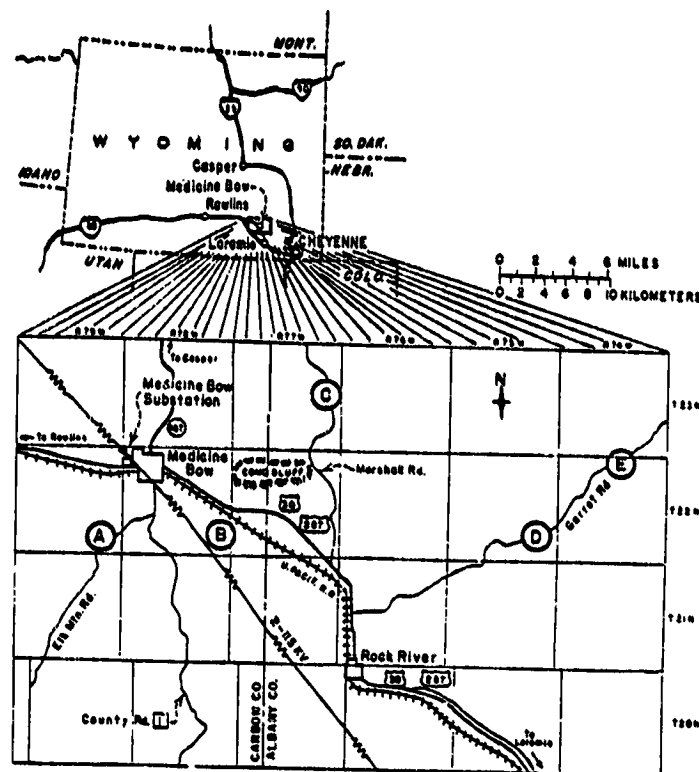
Eight years of wind data taken in the 1930's at the Medicine Bow airport are available. The University of Wyoming, under contract with Reclamation, started taking wind data at the same site in December 1976. At the initiation of the special study in 1977, an area about 32.19 by 64.37 km (20 by 40 miles), as shown in Figure 3, was delineated and five 3.66 m (12 feet) anemometer towers were installed



Location of Wind Resource and Hydroplants  
Figure No. 2

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# WIND/HYDROELECTRIC INTEGRATION STUDY MEDICINE BOW, WYOMING



Study area showing locations of the  
five anemometer towers designated  
A B C D and E.

Medicine Bow, Wyoming, Wind Area  
Figure No. 3

to gather information to evaluate a specific site to install the SVU's. After several months of data collection and evaluation of all factors at the five sites, site A southwest of the town of Medicine Bow was selected to install a 60.35 m (198 feet) meteorological tower, which was later extended to 109.7 m (360 feet) to measure the vertical wind characteristics at three levels. The SVU's will be installed near the meteorological tower.

A computer model of the Medicine Bow wind regime has been developed using the 10 years of data now available to simulate an average wind year by providing the wind speed each hour in the year. Inputting the performance curve from a wind turbine unit, the annual generation can be determined by calculating the output each hour in the year. Figure 4 summarizes the results of inputting the predicted performance curve for the Hamilton Standard WTS-4 wind turbine. The monthly energy production is plotted on a water year, October through September, and onpeak and offpeak generation quantities are shown separately. The total average annual energy production for one unit is 11.9 million kWh. The significant data in this summary are that 69 percent of the generation occurs during onpeak hours and 31 percent occurs offpeak. The onpeak generation has the most value to a power system and makes the resource at the Medicine Bow site highly compatible for integration with a hydrosystem. There is more wind generation during the winter months which complements the hydrosystem which has the greatest generation during the summer due to the spring runoff from the snowmelt in the Rocky Mountains.

#### PROCUREMENT OF WTS-4 WIND TURBINE

Reclamation is a rather large engineering organization that designs and constructs large hydroelectric projects. However, after the decision was made to procure a wind turbine SVU, it was felt that the organization did not have sufficient expertise in the wind technology and assistance would be needed. The National Aeronautics and Space Administration (NASA) was agreeable to provide Reclamation with the support needed to procure a wind turbine and the two agencies executed an interagency agreement. NASA would provide the technical management for the design, fabrication, installation, testing, and initial operation of the wind turbine SVU. Also, NASA would train Reclamation personnel in wind turbine technology.

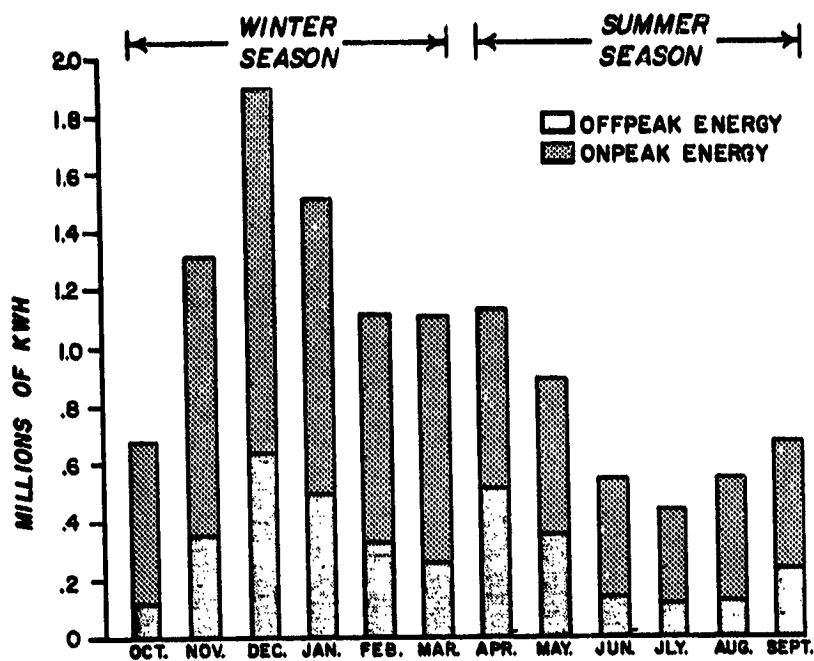
A number of wind turbine manufacturers had indicated an interest in furnishing equipment for the Medicine Bow site; therefore, the decision was made to procure the first SVU by competitive bidding. The chronology of events for the first SVU is as follows:

- |   |          |      |
|---|----------|------|
| 1. Interagency Agreement with NASA signed | May      | 1979 |
| 2. Request for proposals issued           | July     | 1979 |
| 3. Contract signed - Hamilton Standard    | February | 1980 |



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**WIND GENERATION DATA—MEDICINE BOW, WYO.**  
**ANNUAL OUTPUT FOR WTS-4 UNIT**



**SUMMARY**

	<u>WINTER</u>	<u>SUMMER</u>	<u>ANNUAL</u>
ANNUAL ENERGY *	7.7	4.2	11.9
SEASONAL GEN.	64%	36%	
PLANT FACTOR	44%	24%	34%
ONPEAK GEN.	71%	65%	69%
OFFPEAK GEN.	29%	35%	31%

\* MILLIONS OF KWH

<u>PERIOD</u>	<u>WINTER</u>	<u>SUMMER</u>
ONPEAK	7 A.M. TO 11 P.M.	11 A.M. TO 10 P.M.
OFFPEAK	11 P.M. TO 7 A.M.	10 P.M. TO 11 A.M.

Annual Generation Pattern for WTS-4  
Figure No. 4

4. Final design review - Unit	September 1980
5. Final design review - foundation and tower	November 1980
6. Start of construction at site	May 1981
7. Scheduled first rotation	June 1982

#### SITE ARRANGEMENTS

The site plan for the first two SVU's is shown in Figure 5. The area is surveyed for 1 square mile sections. The location for the first SVU is about 8.25 km (5½ miles) southwest of the town of Medicine Bow, situated near an existing county road. The WTS-4 wind turbine is about 251.5 m (825 feet) downwind from the meteorological tower. The prevailing winds are from west southwest at a bearing of about 250 degrees, which provide 90 percent of the generation. The control and visitor center building is near the meteorological tower and near the edge of the development area to minimize visitor disturbance of private land.

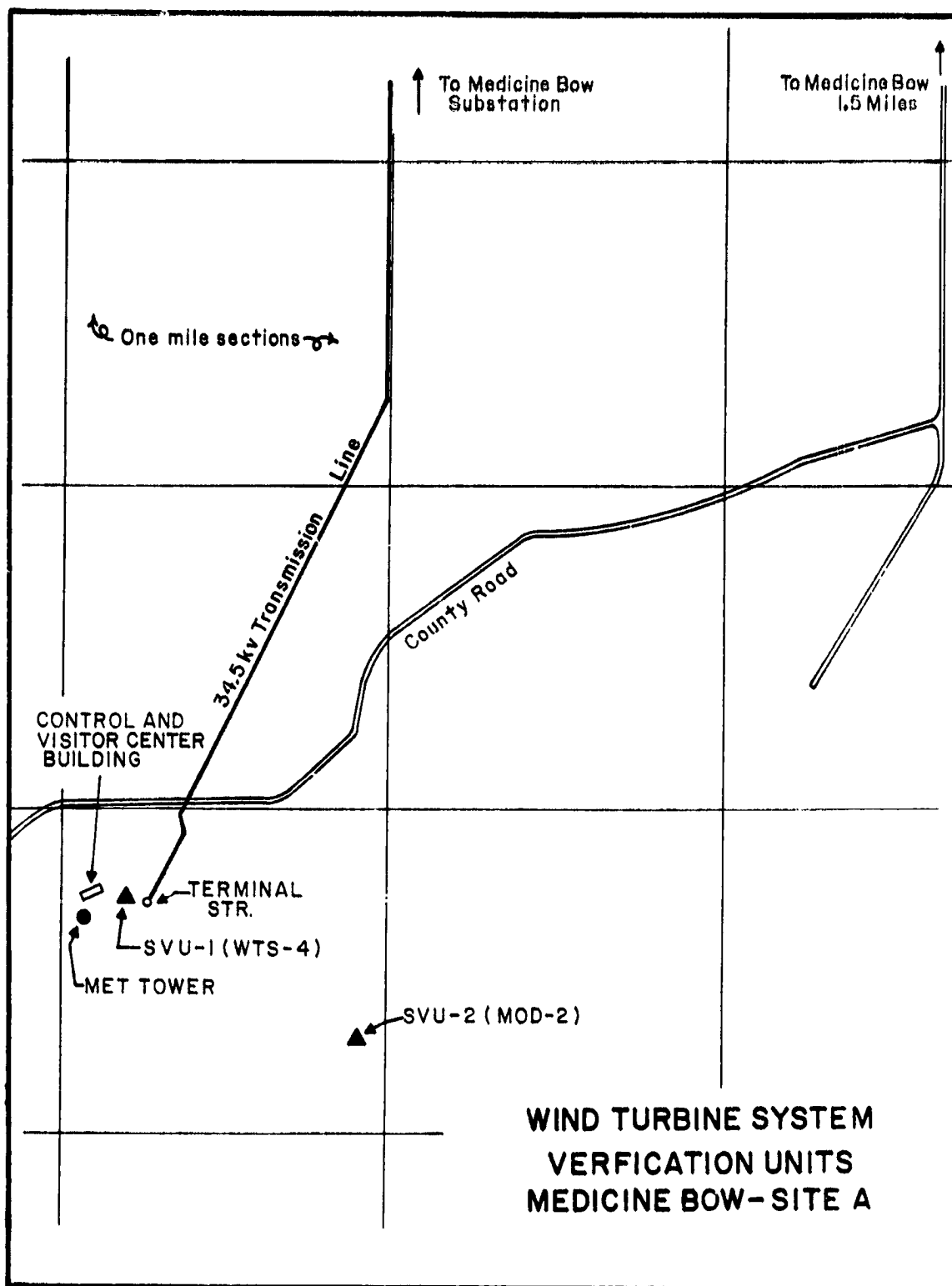
The second SVU, MOD-2, is located 1.37 km (4,500 feet) downwind, 15 blade diameters using 91.4 m (300 feet) rotor, and offset downwind from the first SVU. The 15 diameter spacing was an arbitrary spacing since we do not have specific information on the affects of wind wake produced by large wind turbines. We believe the selected spacing is conservative and hope that more positive data on turbine spacing will be available in the near future before we do the final design on the wind farm. We have awarded a contract to the Scientific Technologist in Pasadena, California, to do a study to assess affects of wind wake from an array of wind turbines. The results of the study will be available later this year.

#### TRANSMISSION SYSTEM INTERFACE

The transmission line is designed for future operation of 115 kV for the wind farm application and will be initially operated at 34.5 kV. The line will be interconnected to the Federal transmission system at the existing Medicine Bow Substation, which is about 8 km (5 miles) north of the SVU's. Since there are eagles and other birds of prey in the Medicine Bow area, the transmission structures will be single pole types, with conductor spacing to prevent eagle electrocution and a raptor antiperch device mounted on top of the pole. The details of a typical structure are shown in Figure 6.

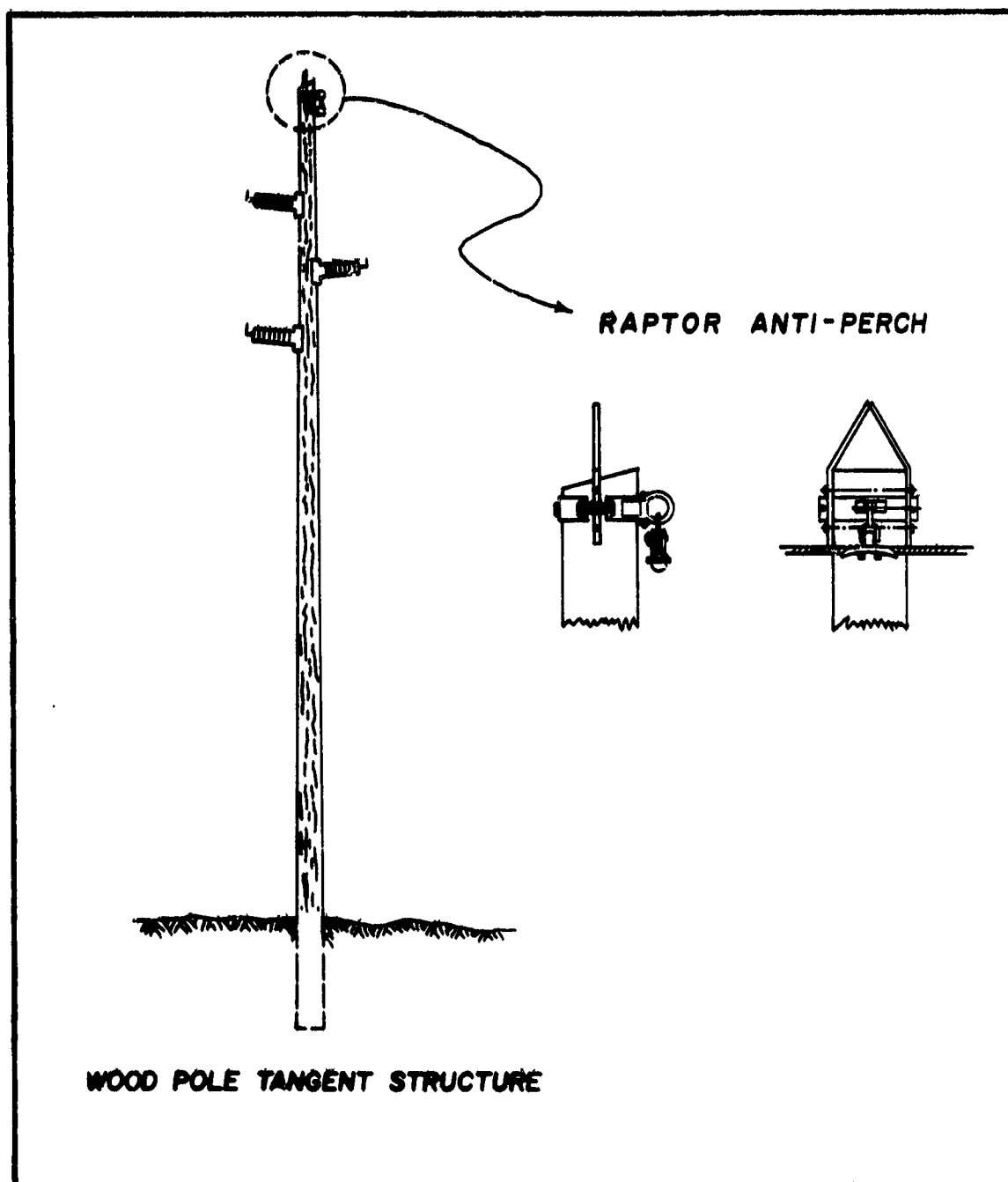
Figure 7 is a perspective view of the site showing the relationship of the turbine, control building, transformer, and switchgear near the base of the unit and the transmission line terminal structure.

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Site Location of Wind Turbines  
Figure No. 5

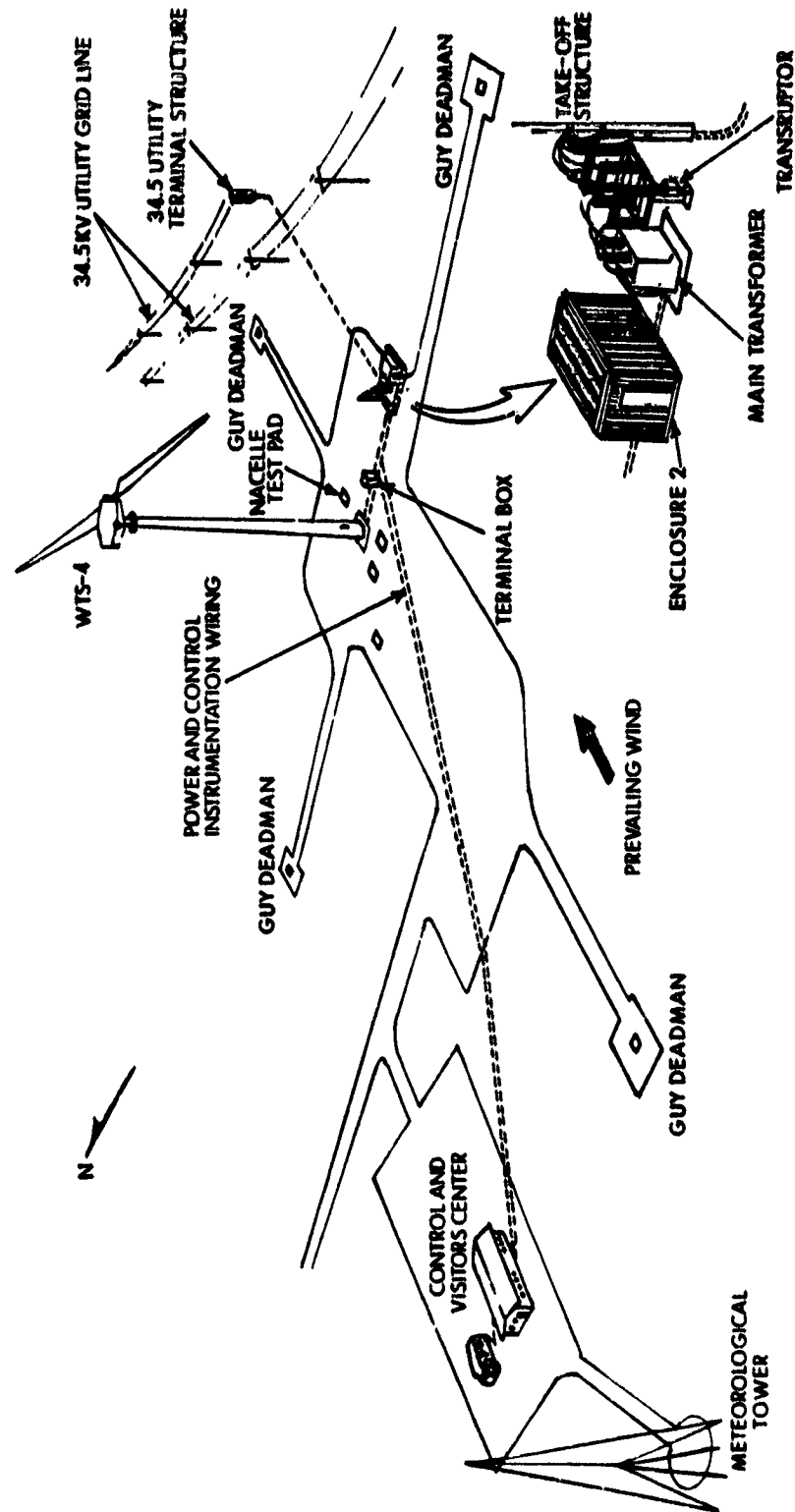
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Typical Transmission Line Structures  
Figure No. 6

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WTS-4/SYSTEM INTERFACE  
PERSPECTIVE VIEW  
MEDICINE BOY, WYOMING



Perspective View of WTS-4 Site  
Figure No. 7

Figure 8 is an elevation view of the power circuit showing the routing of the power cable down the inside of the tower, underground to Enclosure no. 2 that houses the circuit breaker, underground to the 4.16/34.5-kV transformer, through the interrupter switch and then underground, at 34.5 kV, to the terminal structure.

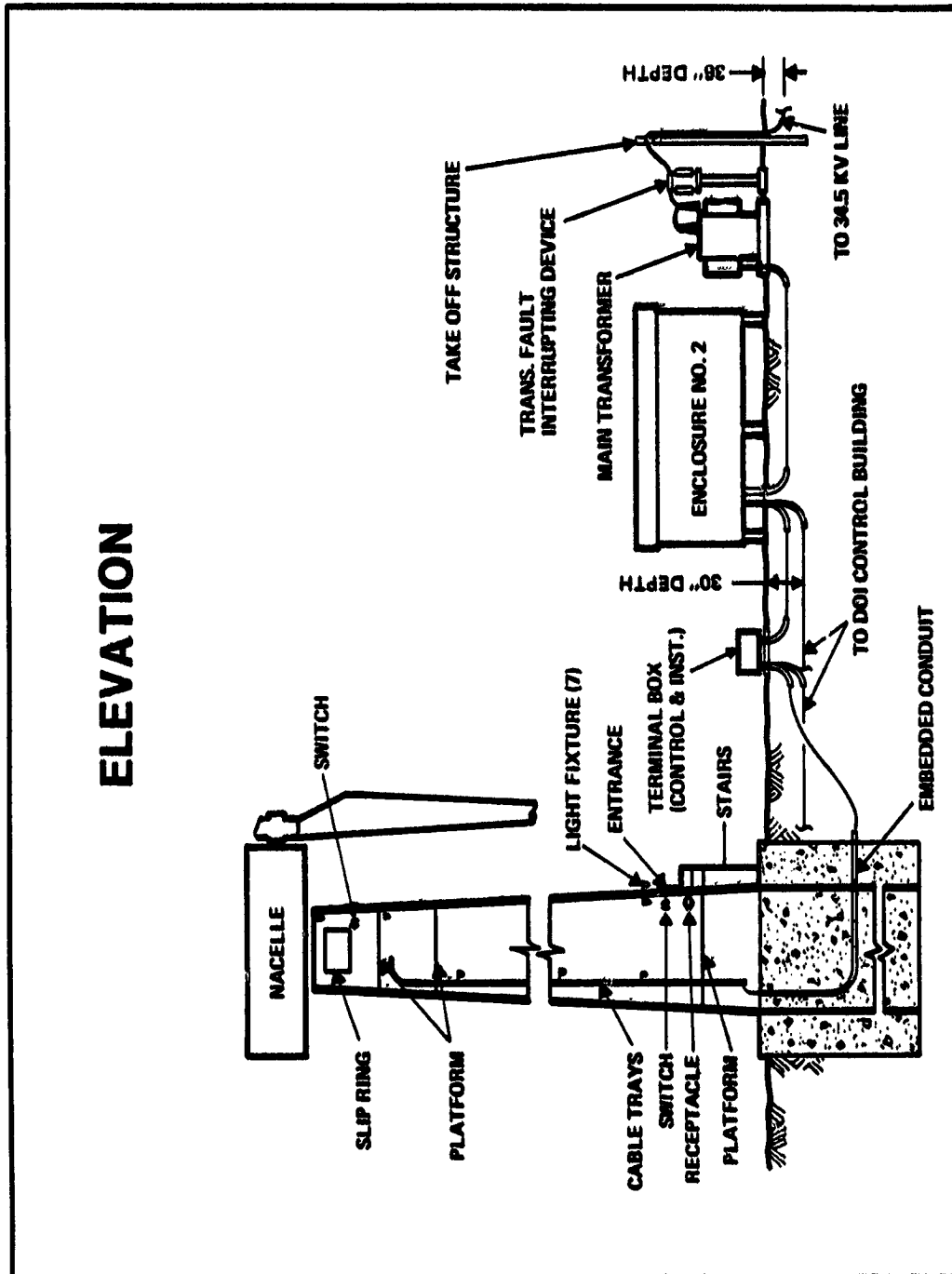
Figure 9 shows a simplified schematic of the power circuit from the wind turbine generator to the interconnection to the transmission line at the terminal structure. Underground power cables were selected to reduce the clutter near the base of the wind turbine and minimize the visual impact from overhead lines. A new transmission line was constructed to serve the SVU's although an existing utility 34.5-kV distribution line is near the site serving loads in the area. The new line dedicated to the SVU's will optimize availability by eliminating the exposure of the longer distribution line. Disconnect switches will be used to interconnect the first two SVU's to the terminal structure. If Congress authorizes the 100-MW wind farm, the turbines will be grouped in clusters of four to seven units for interconnection to the 115-kV transmission line. Reclosures or circuit breakers will be used in each of the turbine circuits ahead of the transformation to 115 kV.

#### SUMMARY ---

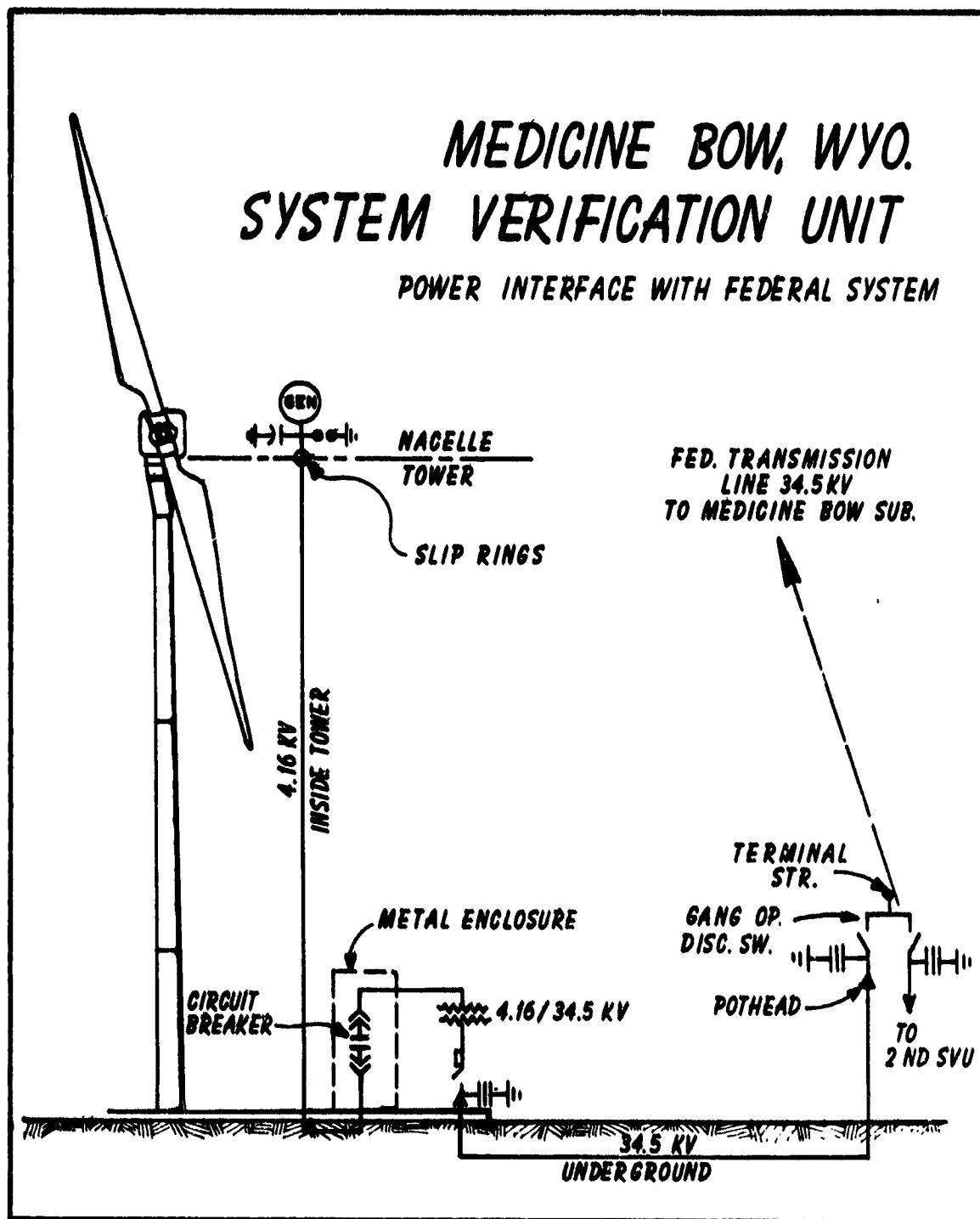
A brief summary of the turbine supplier's progress to date is as follows: The site preparation and excavation for the tower foundation are complete. The fabricated tower sections have been delivered to the site. The fabrication of the first fiberglass blade is complete. The assembly of the nacelle in the Swedish factory is almost complete. Although the scheduled first rotation date of June 1, 1982, has slipped 8 months from the original date due to the accumulation of delays, we believe the design and construction of the WTS-4 will result in a quality product.

NASA's previous experience in managing the Department of Energy's large wind turbine program has been invaluable to Reclamation by providing technical management for the SVU project at the Medicine Bow site.

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WTS-4 Power Circuit  
Figure No. 8



Schematic of Power Interface to System  
Figure No. 9



MIT

## QUESTIONS AND ANSWERS

A. W. Watts

From: F. J. Ahimaz

Q: Why not eliminate the generator unit in the WTG system and use the wind turbine to drive reciprocating pumps instead of centrifugal pumps. It will reduce cost appreciably and will pump water at all speeds of the rotor.

A: *The lowest cost arrangement is to integrate wind energy into the hydrosystem to serve load directly without pumping water which reclamation is using. The best wind site may not be at the location where water is being pumped.*

From: P. Antoniak

Q: 1) What is your operations staffing?  
2) What is your maintenance staffing?  
3) What is the size of your operations building?  
4) What is the size of your maintenance building?

A: 1) *Operations will be performed by the present staff at the Casper Control Center.*  
2) *Maintenance staff will be 3 employees at the Medicine Bow site and other support farm maintenance crews stationed at Casper, Wyoming.*  
3&4) *The operations will be done from the existing building in Casper, Wyoming. The maintenance building at the Medicine Bow site is sized for the two SVU's and a larger building will be built for the farm application.*

From: Anonymous

Q: What are DOI-BuRec plans for expanding the cluster? (How many machines, by when?)

A: *We do not have funding for additional SVU units.*

From: Anonymous

Q: Does the hydro storage become full during the year?

A: *System operations can be controlled so that water does not by-pass the generators even with the wind farm.*

From: A. B. VanRennes

Q: What is the round-trip efficiency factor of hydro storage, i.e. kwh of hydro power received compared to kwh of pumping power expended?

A: *The integration concept does not use the water pumping principle. (See the first question.)*

INITIAL UTILITY EXPERIENCE WITH CLUSTER OF THREE MOD-2 WIND TURBINE SYSTEMS

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 BONNEVILLE POWER ADMINISTRATION  
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 Portland, Oregon 97208

ABSTRACT

This paper describes the initial utility experiences of operating three MOD-2s during the Engineering Acceptance Testing. Electrical quantities of bus voltage, phase currents and power are initially being recorded to evaluate impacts to customers on the 69-kV subtransmission line during synchronization and operation of one or more WTSs. To date, effects on the system have been essentially undetectable.

Measurements of television signal strengths were taken at an existing television remote pickup and relay station at the WTS site. Potential TV signal interference problems from the WTSs have been avoided by replacing the remote pickups with microwave repeater links for the four TV channels received from Portland, Oregon.

Preliminary measurements of audible and sub-audible noise levels indicate that the upwind rotor, tubular tower design of the MOD-2 does not have the pulsing high intensity infrasound problems experienced by the MOD-1 machine at Boone, North Carolina.

Some preliminary assessments have been made on the MOD-2 WTSs in regard to adequacy of emergency shutdown systems and operation and maintenance support activities. Wind Turbine Systems operating on a utility system can experience loss of connection or load and must be able to reliably shut themselves down.

INTRODUCTION

The cluster of three MOD-2 Wind Turbine Systems (WTSs) installed and placed into service at Goodnoe Hills in the Federal Columbia River Power System is the first multiunit wind turbine generator installation which has operated with all generators simultaneously supplying power to a utility electrical power system. Goodnoe Hills is located in Klickitat County in southwestern Washington. The site, at an elevation of 2600 feet, is situated on a ridge north the Columbia River, 7 miles east of John Day Dam and about 13 miles east-southeast of Goldendale, Washington. The MOD-2 units are connected to a nearby 69-kV line owned and maintained by Klickitat County PUD, a customer of the Bonneville Power Administration.

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Paper prepared for the Large Horizontal-Axis Wind Turbine Workshop held in Cleveland, Ohio, July 28-30, 1981, sponsored by DOE and NASA-LeRC.

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BPA's participation in the MOD-2 Research, Development, and Demonstration project provides for the following:

1. Developed site - land, access roads, 69-kV/12.5-kV substation, 3 miles of 69-kV line, microwave radio station, underground 12.5-kV cables, underground telephone cables for protective relaying, control, telephone, data transmission, 198-foot meteorological tower, and Data Acquisition System.
2. Operation and Maintenance.
3. Administrative, Engineering, and Technical Support.
4. Visitors' Center..
5. Mitigation of potential television interference.

BPA started developing the site early in 1980 and Boeing Engineering and Construction Company working to a tight schedule completed construction of the first MOD-2 WTS by December 1980. The other two WTSs were completed within intervals of 3 months.

Initial synchronization of the three MOD-2 WTSs was accomplished on the following dates:

WTS-1	December 22, 1980
WTS-2	April 7, 1981
WTS-3	May 19, 1981

Test activities conducted by BPA since construction of the three MOD-2 WTSs have been primarily concerned with initial efforts to monitor and record the quality of power.

On Tuesday, April 28, 1981, WTS-1 was monitored for 24 hours by BPA power dispatchers via a remote CRT Control Terminal installed at the BPA Dittmer Control Center in Vancouver, Washington, approximately 160 km west of the site.

All three units were operated simultaneously for a brief period on May 27 just before the dedication which was held on Friday, May 29, 1981.

On June 8, WTS #1 failed during a staged emergency shutdown test and details of that incident were covered in other sessions of the workshop. At the time

of failure the three units had accumulated running times and generation as follows:

<u>WTS</u>	<u>Operating Time</u> <u>HRS</u>	<u>Sync Time</u> <u>HRS</u>	<u>Energy</u> <u>MW hr</u>
1	107	84	99.4
2	122	113.5	138
3	19	18.5	23.7

This report covers the following areas of concern to utilities contemplating the use of wind energy on its system. They are:

1. BPA integration facilities
2. Operation and maintenance aspects of large wind turbine complex
3. Utility perspective on the June 8, 1981, failure of WTS #1 at Goodnoe Hills
4. TV signal field measurements and new microwave radio equipment and antennas provided by BPA to avoid potential TV interference problems to the existing Western Telecommunications, Inc. (WTCI) TV facilities.
5. Noise survey conducted by the Solar Energy Research Institute
6. The quality of power

BPA believes that the Goodnoe Hills MOD-2 project will provide an excellent opportunity to obtain valuable utility experience on a cluster of large WTSs as well as essential wind turbine development and demonstration type data.

#### BPA INTEGRATION FACILITIES

As shown in Figure 1, the three MOD-2 units are connected to an existing Klickitat County PUD 69-kV transmission line located 3 miles north of the Goodnoe Hills site. BPA constructed a 10 MVA 69-kV/12.5-kV substation at Goodnoe Hills and the 69-kV tap line. Each WTS is connected to the Goodnoe Hills Substation by three single phase cables, each shielded with an outer armour ground, and a 4/0 ground mat tie conductor at the bottom of a sand-filled trench. The generator terminal voltage is 4160 volts. The 4160 volt bus tie contactor, step-up 4.16-kV/12.5-kV transformer and metering are located in a metal enclosure on a concrete pad next to each tower. At the Goodnoe Hills substation, fuses and disconnects are provided on the 69-kV side and one circuit switcher on the 12.5-kV side.

Underground telephone cables have been installed between the Goodnoe Hills Substation and each WTS and the microwave radio station. Communication circuits have been provided for the following services and systems:

1. Dial Automatic Telephone System (DATS) over the BPA Microwave Radio Communication System. A 6-button telephone set has been installed in each WTS Substation, Data Building, and Radio Station. The telephone system provides connection to the local central office telephone line and intercom service.
2. Remote control of WTSs is from BPA's Dittmer Control Center located in Vancouver, Washington. Three CRT remote computer control terminals are installed at the Dittmer Control Center. The three control channels are submultiplexed on one microwave radio communication channel.
3. Data Channel. The data from the minicomputer PDP-11/34A in the data building located near the base of WTS-2 will send data by microwave radio to an existing Data Acquisition System located in Portland.
4. Power Circuit Breaker (12.5-kV PCB) disabling circuit. Synchronizing of the WTS to the power system is done with the Bus Tie Contactor (BTC) at the base of the tower. The 12.5-kV PCB at Goodnoe Hills Substation cannot be closed unless all of the BTCs are open.

The addition of WTSs on the 69-kV Feeder required modifications to be made at the BPA Chenoweth and Klickitat County PUD Goldendale Substations. The modifications included:

1. Install "hot line" check relays and modify PCB automatic reclosure. The WTS must be disconnected from the power system before any of the 69-kV or 115-kV PCB can be reclosed.

#### OPERATION & MAINTENANCE ASPECTS OF A LARGE WIND TURBINE COMPLEX

Early experience with the MOD-2 complex at Goodnoe Hills indicate that wind turbine system designers should pay close attention to the operation and maintenance support aspects of the complex, particularly from a utility standpoint. In regard to the Goodnoe Hills complex, the nearest BPA maintenance personnel are located at BPA John Day Substation approximately 40 miles away (1 hour driving time). The complex has limited storage space, so the bulk of warehousing of turbine spares, etc., is maintained off-site at The Dalles, Oregon, approximately 50 miles away. The logistics of supporting necessary operation and maintenance activities with the transit times involved can well be imagined. BPA is working with NASA and Boeing in developing plans to provide necessary O&M support in an efficient manner. Monitoring systems that permit off-site diagnosis of wind turbine problems prior to dispatch of maintenance personnel is one area which should be addressed by wind turbine designers in laying out future remotely operated complexes.

The WTSs (and other customers) are protected from abnormal operating conditions by use of suitable relaying equipment.

An alarm should be provided for each remote CRT control terminal to alert the operator when the communication or control circuit becomes disabled.

#### UTILITY PERSPECTIVE ON THE JUNE 8, 1981, FAILURE OF WTS #1 AT GOODNOE HILLS

The failure of WTS #1 on June 8 (details of which were covered in more depth in earlier sessions) pointed out the need of having reliable, redundant emergency shutdown systems on large wind turbines. From a utility perspective, BPA is concerned that the MOD-2 units (or any large wind turbine employed on our system) be provided with "in-depth" redundant protective failsafe shutdown systems similar in philosophy to those developed by the utility industry for other prime mover systems.

Specifically, BPA has recommended to the NASA and Boeing investigative teams analyzing the WTS #1 failure the following:

1. Installation of "in-depth," maintainable, emergency shutdown systems on all MOD-2 wind turbines. The systems should be independent, redundant systems designed such that any common-mode failure of the electrical-hydraulic systems will not prevent safe shutdown of the wind turbine system.
2. General refurbishment and/or upgrading of electrical control system components.
3. Redesign of O&M procedures in regard to emergency shutdown systems.

These recommendations are being evaluated by the investigative teams. Hopefully, the modifications that are implemented on the units as a result of the incident will reflect the utility philosophical approach to prime mover protection.

#### TV FIELD MEASUREMENTS AND NEW MICROWAVE RADIO FACILITIES

Possible TV interference to the Western Telecommunications, Inc. (WTCI), existing CATV facilities at Goodnoe Hills was recognized by BPA.

WTCI operates a marginal system installed in 1963 which consists of "off the air" antenna reception of television channels 2, 6, 8, and 12 from Portland, Oregon. The TV channels are retransmitted by microwave radio to some seven eastern Oregon communities.

TV field measurements were made on February 12 and 13, 1980. The received signal strength at the time of the test, on all channels, was less than the ideal 500 microvolts (field intensity measurement) desired at the receiving antenna site with reference to a high-gain yagi antenna. At the time of the test, measurements of 140 to 190 uV were obtained at the channels 2, 8, and 12 antenna location and 350 uV at the channel 6 antenna location. The channel 8 video information was receiving some TV channel 7 audio interference from a station of unknown location. This may explain the periodic channel 8 interference noted during video tape recording in the WTCI station. Channels 6 and 12 in the WTCI station have some periodic ghosting problems as can be observed on the video tape recording.

Because of ghosts the best location for "off the air" antenna reception of Channel 6 found by WTCI was in a ravine northwest of WTS-2 . . .

To preclude any possible TV interference from the rotors of the MOD-2 units the four TV receiving antennas have been relocated. TV channels 2 and 6 are now being picked up at Scapoose, Oregon, and relayed to Goodnoe Hills via a WTCI microwave radio repeater station at Mt. Defiance about 58 miles west southwest of the site. TV channels 8 and 12 are picked up at Mt. Defiance and relayed by microwave radio to Goodnoe Hills. BPA paid WTCI \$162,412 for the new facilities. The modified system for WTCI is operating satisfactorily.

Planned static and dynamic measurements of TV scattering from the MOD-2 blades of signals originating from Portland about 160 km away have not been completed. Tests are planned to be made to

- a) determine the TVI at the TV channel 6 location near WTS-2
- b) determine the TVI at the TV receiving antennas for channels 2, 8, and 12 located 1/2 miles south of WTS-1
- c) determine the equivalent blade scattering area of MOD-2.

BPA also made TV field measurements at the Jones residence about 3/4 mile north and 1000 feet below the WTS site, "cluster" home sites about 2 miles west of the site and at Nacelle height of WTS-1. The signals at the home sites are below FCC Grade B and considered by BPA to be "arbitrary Grade D" or less. <sup>1/</sup> TVI to the residences is not expected and no complaints have been received.

1/ IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 1 Jan/Feb 1980 Page 373.

#### NOISE SURVEY OF MOD-2 WTS-1 BY SERI

Personnel from the Solar Energy Research Institute (SERI) made noise measurements during February 1981 with WTS-1 operating. SERI's plans for more elaborate measurements with three MOD-2 units, previously scheduled for July 16, 1981, have been postponed indefinitely due to overspeed damage of WTS-1 on June 8, 1981.

The following are excerpts from the SERI report:

"A preliminary noise survey was made February 24, 1981, at Goodnoe Hills, Washington, using the Turbine No. 1 MOD-2 Wind Turbine Generator (WTG). The results of this highly preliminary survey show that, in the average, the acoustic output of the MOD-2 is totally broadband in nature, with no strong periodic components. . . The sound produced by the MOD-2 has been described as a "heavy whoosh." This noise does not appear to be correlated with the passage of the blade past the tower and probably is due to random turbulent eddies passing through the blade disk. . . SERI field personnel reported that the "whoosh" could be heard clearly up to about 30-45 m (100-150 ft.) away from the turbine, however, as the distance from the machine is increased further, the "whoosh" is rapidly covered by wind noise."

An assessment of the preliminary noise survey of the MOD-2 wind turbine has been completed with following results:

"The turbine noise at 1-1/2 rotor diameters downwind (450 ft.) is largely composed of incoherent, broadband rotor noise whose peak energy is confined to frequencies below 20 Hz. The sound pressure levels, as determined from this small sample, do not appear excessive and compare favorably with measurements of other turbines when impulses were not present. No strong periodic impulses were found similar to those characteristic of the MOD-1 turbine. "

It is to be noted that the "heavy whoosh" reported by SERI and heard by any others is caused largely by the unstreamlined tips. If streamlined covers were to be fabricated and installed on the tips the noise level would probably be reduced significantly.

#### QUALITY OF POWER

##### Northwest Power Pool Voltage Schedules

In order to provide voltage compensation on the Northwest Power Pool transmission system the transmission voltage levels are adjusted four times each day.



### Monitoring of Bus Voltages

Both circular and strip chart recording voltmeters have been installed and maintained to monitor bus voltages at the BPA and Klickitat County PUD substations. The recording voltmeters are located at the substations listed below and are shown in Figure 1 Utility System One-Line Diagram Goodnoe Hills.

	<u>Substation</u>	<u>Bus Voltage</u>
1.	Goodnoe Hills (BPA)	12.5 kV
2.	Goodnoe Hills (BPA)	69 kV
3.	Dot (KCPUD)	69 kV
4.	Goldendale (BPA)	69 kV
5.	Chenoweth (BPA)	115 kV

Table I is the schedule of voltages for Big Eddy Substation 115-kV and The Dalles Dam Power House 115-kV bus.

TABLE I VOLTAGE SCHEDULE

<u>STATION</u>	<u>Bus kV</u>	<u>HI</u>	<u>MED</u>	<u>LOW</u>
The Dalles Dam	115	121	119	118
Big Eddy Sub	115	121	119	118

Figure 2 - Goodnoe Hills Substation Voltage Chart 69-kV 4/20/81 and Figure 3 - Dot Substation Voltage Chart 69-kV 4/20/81 show the changes in bus voltage when WTS-2 and WTS-1 were synchronized to the power system. The bus voltage increased about 0.9 percent when the WTS was supplying power. The generators are equipped with both voltage regulators and power factor controllers in the generator excitation system. Only the power factor controllers have been used. The generator power output has been maintained at unity power factor.

Two circular recording voltmeter charts, i.e., Figure 4- Goodnoe Hills Substation Voltage Chart 12.5 kV April 15-21, 1981, and Figure 5 Goldendale Substation Voltage Chart 69-kV April 9-21, 1981, show the scheduled voltage compensation.

Between April 16 and June 2, 1981, there were 79 operating periods varying from 1 minute to nearly 12-1/2 hours. Of these periods, 51 or 65 percent created no detectable change in voltage. Twenty-eight, or 35 percent, created changes of from 0.2 to 0.8 percent with the average change being 0.35 percent.

The effect of WTS on the Goodnoe Hills bus voltage is minimal and less than the scheduled change. At Goldendale Substation since the bus is much "stiffer" the effect of operation of the WTSs is much less perceptible. The typical variation of bus voltage due to loads coming on and going off masks any voltage transients that occur when a WTS is synchronized and operated with varying wind speeds.

The voltage disturbance at Goodnoe Hills and Dot Substation was minimal each time a WTS was synchronized or removed from service, generally less than one half of one percent (0.5%).

Neither BPA nor Klickitat County PUD has received complaints about abnormal voltage dips or service interruptions that could be associated with the MOD-2 complex operation.

The corresponding voltage changes at the Dot 69-kV Substation were essentially the same as at the Goodnoe Hills Substation on the 69-kV side.

#### Noise Spectra on the Bus

Noise spectra data of bus voltage was recorded at Goodnoe Hills Substation on June 10, 1981, without any of the WTSs in operation. Further on-site spectral data and other data will need to be obtained with the WTSs in operation. The data will be used to analyze possible interactions between the Goodnoe Hills MOD-2 WTS and the natural dynamic modes of the Western Power System which vary from 0.2 to about 1 Hz at various times of the day and year.

BPA engineers have analyzed system dynamics and report the following with respect to Goodnoe Hills. 2/

". . . Conditions at Goodnoe were inspected while the wind turbines were off-line, which gave no information about the actual degree of coupling there. Further on-site spectral analysis with some machines in operation, and additional operating records, should enable this to be estimated. . . .

The information at hand is by no means complete enough to indicate the extent to which these or related interactions are, or could become, "adverse". Some extrapolations about impact upon MOD-2 performance and security seem reasonable, however:

1. Intermittent power system oscillations at frequencies near that of the quillshaft mode might produce unnecessary tripping of the MOD-2 unit(s), but probably would not be of sufficient magnitude or duration to degrade shaft longevity. Such tripping, if it occurs, would probably be too infrequent to justify revision of unit protection or reclosure schemes.

2. Coupling of the persistent 0.35 Hz power system activity into the MOD-2 machine controls (e.g., for blade angle) may produce appreciable wear and fatigue to mechanical elements. If this is found to be the case then revisions of the machine control logic may be in order."

2/ Ref: Memo by J. F. Hauer to E. J. Warchol dated June 23, 1981, Subj: Possible Interactions between the Goodnoe Hills MOD-2 WTS and Natural Dynamic Modes of the Western Power System.

#### SUMMARY

No adverse power transients were observed during synchronization of the WTSs. During operation from no load to full load the changes in bus voltages were minimal and well below the scheduled voltage adjustments. The WTS generator is equipped with both voltage regulator and power factor controller. The power factor controller was used during the Engineering Acceptance Tests to maintain the generator power output at unity power factor.

TV interference and noise from the MOD-2 WTSs are not expected to present problems at Goodnoe Hills.

WTS-1 which was damaged on June 8, 1981, during a brief overspeed incident is being repaired and will be ready for more tests in March 1982. Units 2 and 3 are expected to be back in operation in late September 1981. A careful and thorough examination of the emergency shutdown philosophy and associated systems by NASA, Boeing, and BPA is currently under way. BPA will recommend that several load rejection tests under different wind conditions should be included in the Engineering Acceptance Tests to demonstrate the reliability of the normal and backup emergency shutdown systems.

Operation and maintenance aspects of wind turbine complexes will be thoroughly analyzed so the complex can be supported in an efficient manner.

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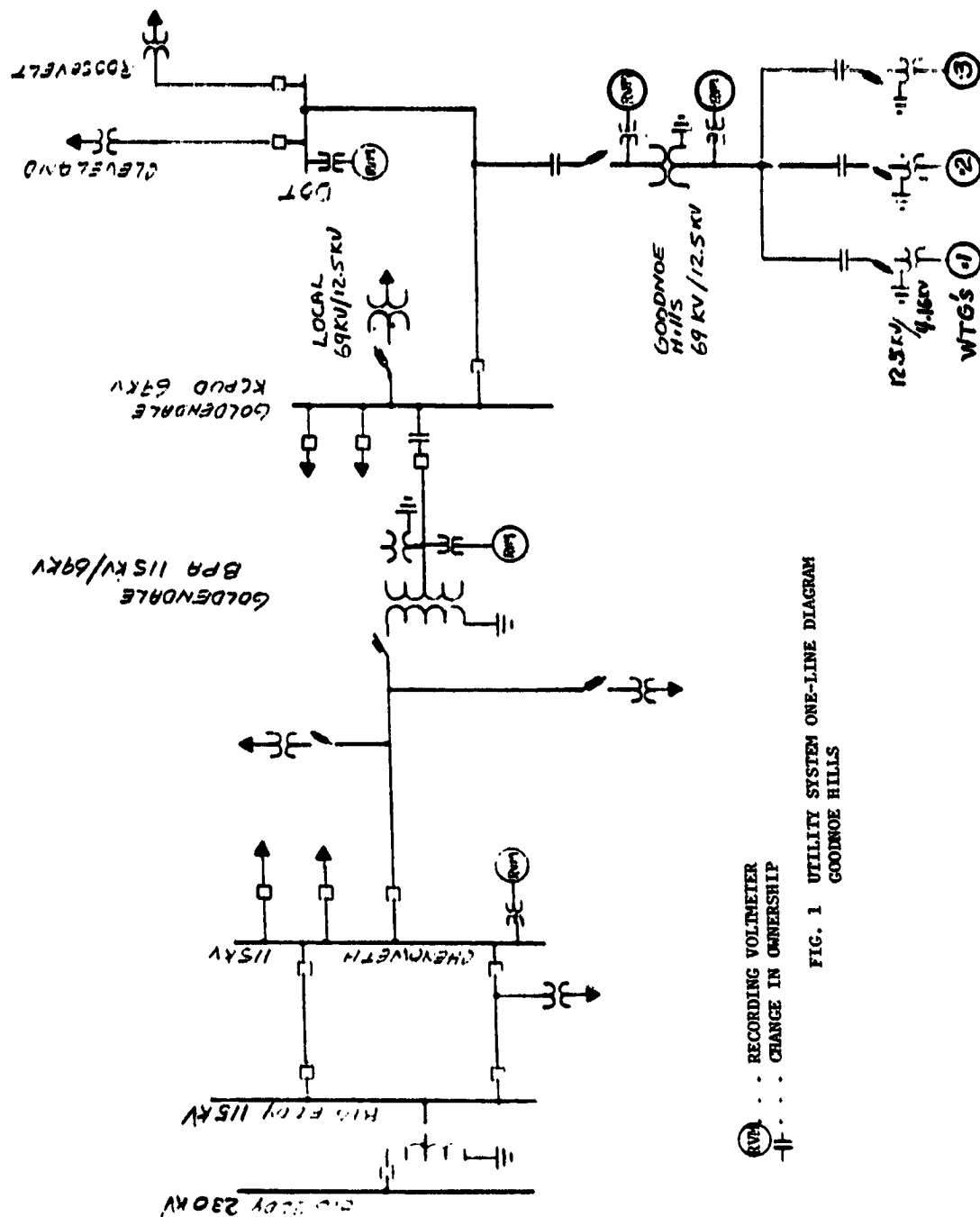
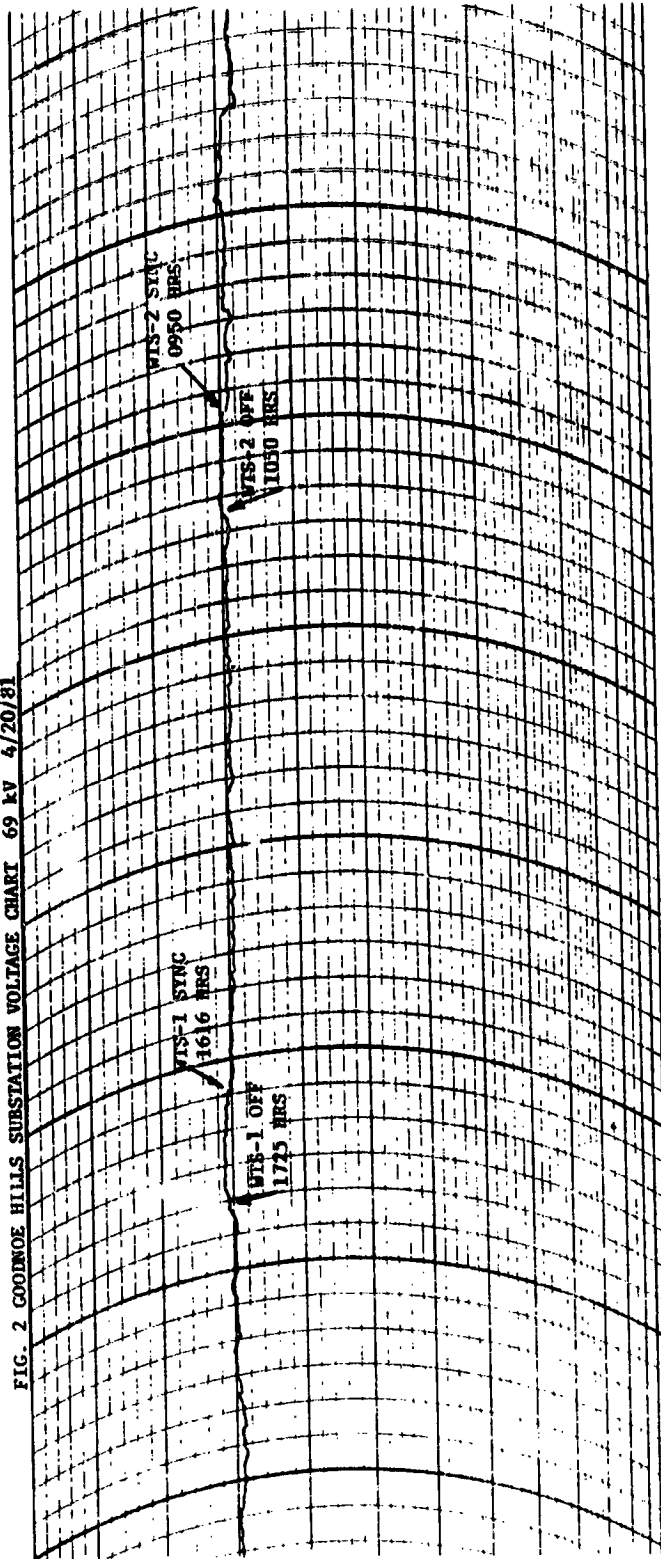


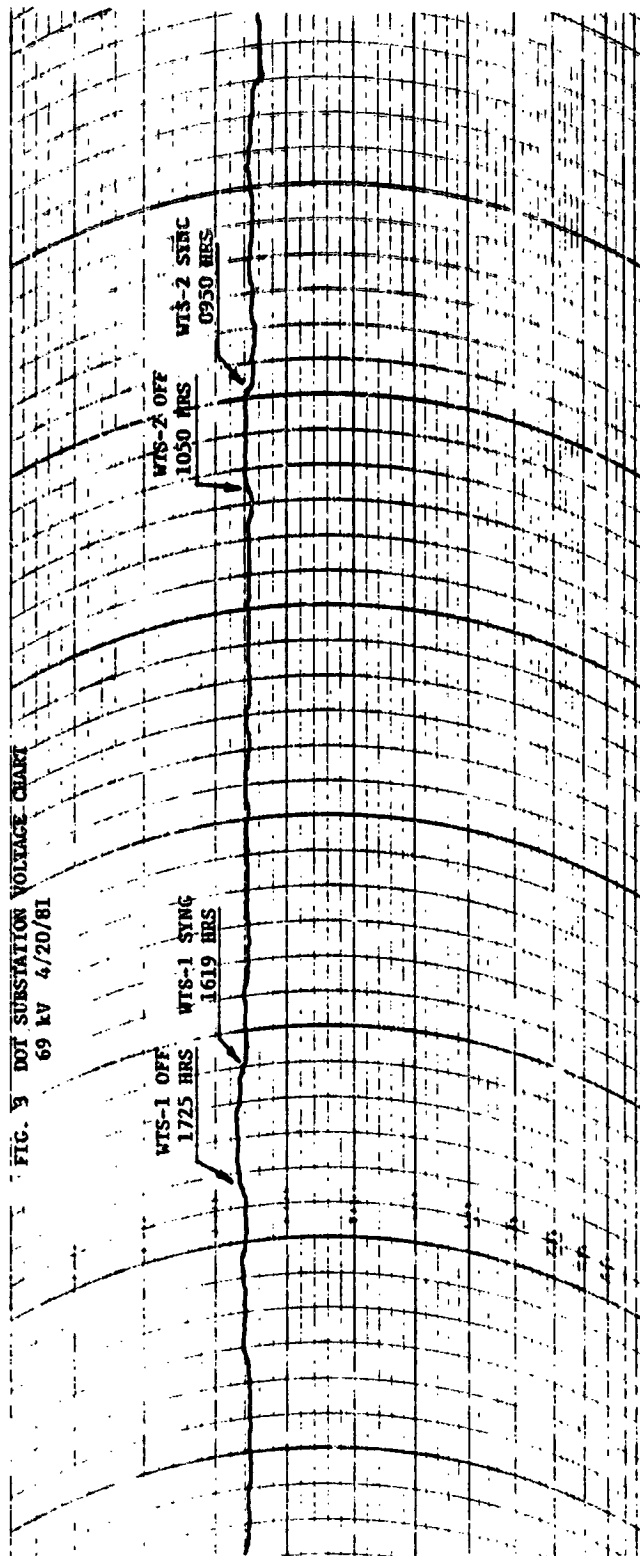
FIG. 1 UTILITY SYSTEM ONE-LINE DIAGRAM  
GOODNOE HILLS

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FIG. 2 GOODNOE HILLS SUBSTATION VOLTAGE CHART 69 KV 4/20/81



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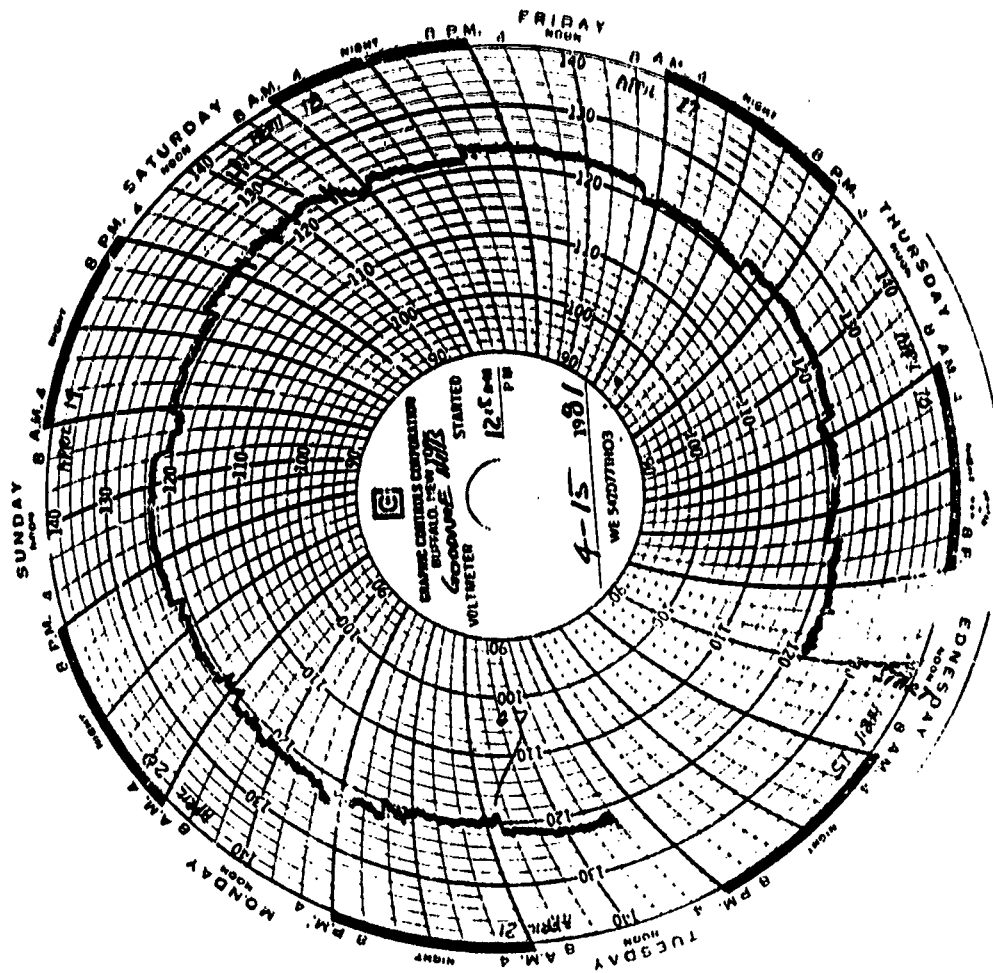


FIG. 4  
GOODNOE HILLS SUBSTATION  
VOLTAGE CHART 12.5 kV  
APRIL 15-21, 1981

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A REVIEW OF UTILITY ISSUES FOR THE INTEGRATION  
OF WIND ELECTRIC GENERATION\*

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ABSTRACT

A review of issues and concerns of the electric utility industry for the integration of wind electric generation is offered. The issues have been categorized in three major areas: planning, operations, and dynamic interaction. Representative studies have been chosen for each area to illustrate problems and to alleviate some concerns. The emphasis of this paper is on individual large wind turbines (WTs) and WT arrays for deployment at the bulk level in a utility system.

INTRODUCTION

The primary issues and concerns regarding the integration of wind electric generation into utility systems can be classified into three major categories: planning, operations, and dynamic interaction. Planning involves an assessment of the feasibility of including wind energy conversion systems (WECS) in the future generation mix of the utility. Operational issues focus on the dispatch of generating facilities with primary concern on the impact of the variable output power of WT arrays on the utility system, including the real-time control and the economic dispatch of both the conventional and the WT units. Dynamic interaction is concerned with the oscillations of power, voltage, and frequency between the WT and the other generating units in the utility system.

The activities within planning, operations, and dynamics span a wide time frame ranging from seconds to years. Dynamic interaction is confined to time frames of milliseconds to minutes while operational issues cover the dispatch of WT arrays and conventional generation

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units spanning time from seconds to days. Generation and transmission planning, on the other hand, is normally performed for a period that is years in the future.

The purpose of this paper is to focus on the critical utility issues within planning, operation, and dynamics as they relate to WECS integration. This document can serve as a guide to understanding utility system concerns, not solving them; and hence it should be useful to utilities, WT designers, and other organizations that are interested in wind electric generation. Representative studies, either completed or ongoing, have been chosen to illustrate potential or observed problem areas as well as indicate how some of the problems have been resolved. The emphasis is on individual machines or arrays that are connected to the bulk transmission network, a likely utility application. Those studies that are associated with the mechanical properties of WECS, WT design and small customer-owned WECS are not considered.

## PLANNING

The purview of electric utility system planning includes the totality of the system: generation, transmission and distribution. This discussion focuses on large wind electric systems that are deployed as single units or arrays connected to the bulk transmission system, hence distribution planning is omitted. Distribution planning is a key issue for non-bulk intertie.

### Transmission

The primary issues facing the integration of WT systems are within the generation planning framework, however, transmission planning does require some discussion. In transmission planning, capacity requirements and overall system stability are dominant considerations. From the perspective of the transmission system, electric production from present designs of WTs is no different from production from conventional generation, hence present transmission design practice is adequate. The transmission capacity requirements are determined by the relative geographical location of the generation and the load and to the total power transport requirements. Two studies [1,2] have considered transmission capacity needs and have shown those needs fall within normal requirements of transmission design. Since, the transmission system is also vital to overall system stability and is critical when generators oscillate against one another, two studies [1,2] have considered these needs and have found no unique transmission requirements to accommodate a WT array. In general, present WT designs have very little, if any, unique influence on transmission plans thus relegating most efforts to engineering design solutions.

## Generation

Electric utility systems are designed to operate at minimum cost with a prescribed level of reliability. In order to meet these goals, a generation expansion plan for capacity additions is devised to meet the next increment in load growth by minimizing the total cost, i.e., the capital, fuel, operating, and maintenance costs. The planning horizon is a multi-year evaluation, typically 30 years in length. Since many years are spanned in the evaluation, "present worth" or discount of future costs is used to determine the total costs. Typically, several generation expansion plans will be tested to determine the most viable option while recognizing that the least cost choice must satisfy the reliability requirements.

The key requirement in the expansion plan is the least total cost over the planning period. Therefore, the capital cost of various generating unit types must be weighted against the costs to operate these units. The "trade-off" is typically determined by assessing the cost of production by dispatching a given generation expansion plan against an hourly load profile over the planning period. An iterative search is performed by varying the unit types while meeting the load requirements on an hourly basis.

Simultaneously, the reliability requirements are assessed. Since all generating units exhibit some unplanned outage time, the need exists to plan for generation in excess of load to cover the contingency for loss of generation. The planning criteria is the commonly used index for generation system reliability, the loss of load probability (LOLP) which is the probability that load exceeds the available generation. LOLP is used to indicate the expected number of events in which load is greater than generation.

There have been many studies examining the impact of wind energy on electric generation planning, far too many to enumerate here. In general, these studies [3-6] have focused on modifying present generation expansion assessment methods to include wind electric systems. The key to establishing the value of wind electric generation to electric utility systems is the identification of factors such as timing of energy production, correlation between energy production and load, etc., which affect total system performance. The impact of these factors is influenced by both the assessment methodology and the economic assumptions. A review [7] of most of the methods has been published and is recommended reading in this area. Additional work remains for improving the effectiveness of conventional models, however, new techniques for assessing the value of non-conventional technologies such as wind is needed.

A planning manual [8] for evaluating the worth of WECS to utility systems has been developed as an aid to utility managers, planners, engineers, and consultants. The approach is consistent with or is an extension of present utility generation planning methods with particular emphasis on how wind can be considered as a generation source. A two-step approach is used in the manual. The first step is a preliminary evaluation of WECS value requiring many simplifications with the

result strongly dependent upon the average annual wind velocity in the general service area of the utility. The first step is intended to inform the user if a detailed evaluation is warranted. The second step is a detailed evaluation including all the conditions planners have found necessary for successful generation planning and the removal of the simplifying assumptions used in the preliminary evaluation.

Uncertainty in the planning of utility systems with WECS has focused on cost and performance of wind turbines. Although a number of experimental machines have been deployed in the field, in general, data from non-research activities is needed. One study [9] suggests that most cost data to date has failed to account for all the WT installation, land, interconnections, transformers, protection equipment, project maintenance, O&M, etc. Most planning studies have used non-site specific data and have resulted in capacity factors for machines larger than those observed in practice [5,10]. Better data on cost and performance of WECS will become available as utilities gain installation and operating experience.

A good overview of the economics and development status of WTs is provided in a DOE/NASA report [11]. Wind turbines were shown to be more economical when arranged in clusters of 25 or more units. The major difference between the 25-unit cluster and a single unit is labor, operation, and maintenance costs. Also, the availability of a WT array for energy production was estimated higher than that of a single unit.

One of the first steps in evaluating the potential of wind energy is to determine the wind characteristics of potential sites. Hourly average wind data at potential sites is needed, however, it is often not available. This is a major difficulty in performing economic dispatch planning assessments. Several sources for wind data do exist, including monthly average wind power for 101 sites [12]. Information on wind is also available from Battelle Pacific Northwest Laboratory reports [13,14].

#### DYNAMIC INTERACTIONS

An electrical power system is in a state of constant dynamic motion resulting from load changes, changes in production level at various power plants, and network switching. In general, these perturbations cause excursions of power, frequency, and voltage at the system's natural frequencies of oscillation which are usually sufficiently damped to prevent a sustained system oscillation or one that grows with time. Systems exhibiting these properties are said to be stable. The addition of WTs could over-excite normal, highly damped modes or excite new modes resulting in utility system stability problems. It is important to distinguish between system and WT instabilities since the former could severely restrict the use of WTs by utilities.

Fluctuations in wind velocity result in variations in WT output which could cause severe system power swings, frequency variations, and/or system instability. The severity of the problem is determined from a combination of generation mix and type, load profile, and overall

operational procedures. Dynamic and transient analyses on the impact of WT variations on utility systems have been performed in several studies [15-18]. An early GE study concluded that WECS were marginally stable with moderate wind gusts and exhibited unacceptable voltage and power angle oscillations with severe gusts [15]. The study recommended stability improvement measures which were considered in later design studies for advanced WTs. In general, utility system stability has not been threatened by WTs.

The dynamic and stability properties of large modern wind turbine generators connected to power systems has been studied by Hinrichsen and Nolan [16,17]. It was shown that the dynamics of WTs are dominated by the torsional characteristics of the drive train. WTs have a relatively soft shaft that has a decoupling effect on electrically and mechanically produced transients. The unusual torsional system characteristics of wind turbines provide the ability to synchronize a WT through large phase and speed mismatches, however, its transient stability properties under automatic circuit breaker reclosing is poor. No adverse interactions were found for groups of WT units synchronized together. The dynamic behavior of multiple machines was found to be similar to that of a single machine.

The two most severe electrical disturbances for the WTs are short circuits in the vicinity of the generator terminal and complete loss of load followed by subsequent restoration of load [17]. Both disturbances result in large electrical transients.

During a loss of load, the generator rotor moves quickly away from the synchronous reference position. However, the turbine which is coupled to the generator with a soft shaft continues to operate close to synchronous speed. If resynchronization is attempted under these conditions, large electrical transients result. Since the mechanical stiffness is much lower than the electrical stiffness, electrical transients result in large forces on the generator windings. Studies at Purdue University found that arbitrary reclosing should not be employed [18]. A modified WT hub speed control is suggested for reclosing and reloading the machine. Special protection practices must be developed to prevent mechanical damage to the WT generator. The development of protection guidelines is the objective of several present studies.

The dynamic impacts of large penetrations of wind generation on the Hawaiian Electric Company (HECO) utility system was assessed by Zaininger and Bell [2]. No stability problems resulted from adding 80 MW of wind generation capacity to the HECO system although the WT array generator equivalent was found to be very active after a disturbance due to the very small shaft inertia compared to that of conventional generators.

WT dynamic impacts are a subject of continued investigation. The Electric Power Research Institute is funding a research effort to develop a methodology for determining the dynamic impacts of wind turbines on utility systems.

## OPERATIONS

Electric utility operations cover a wide range of functions, including operations planning, economic dispatch, frequency control and load following. These functions are affected by a combination of level of penetration as a percent of instantaneous load and when the WT production occurs. A number of measures for penetration have been employed such as percent of peak load, percent of dispatched generation, percent of peak capacity, etc., however, most of these measures are ineffective in capturing the essential factors affecting power system operations. At modest levels of penetration relative to system load, the impact of WTs has been small [19], however, the type of generation, small diesels, is a significant fact. As penetration levels are increased, the variable nature of wind plant production could have significant impact on the operations of the utility system such as excessive ramping of generators and unacceptable frequency variations. Many of these impacts will tend to economically limit the practical penetration levels of wind generation for utility application.

### Unit Commitment and Economic Dispatch

An important aspect of power system operations is pre-dispatch or unit commitment. This aspect of operations planning schedules production on a one to three day time horizon in anticipation of load level and reserve requirements. The power plants are then economically dispatched, typically on 10-30 minute basis. The affect of WTs on these two processes has not been fully investigated. One study [1] in progress is investigating the impacts on unit commitment.

The economic dispatch issue will be considered as utility data becomes available from sites where cycling of power plants might disrupt normal dispatch levels. The effect of wind generation penetration on total system operating costs is a combination of dispatch policy and unit sizes. For a specific generation mix there is a maximum penetration level of WTs that can be optimally accommodated. Beyond that maximum penetration level, the cost penalty is greatly increased by a departure from the optimal dispatch of the generation as imposed by the increased load following requirement.

### Load Following and Frequency Control

The cyclic variations in load require the capability to cycle power plants such that a high quality of electricity is maintained, i.e., proper frequency and sufficient capacity. Thus, power plants must have sufficient response capability to follow load both in magnitude and rate of change. Typically, these needs are met by distribution of the system's instantaneous load carrying capability among several units. It is desirable to limit the number units for load following since the economic operation of the plants is compromised in this mode. Clearly, WTs could add to the load following requirements of the conventional plants.

A number of studies have shown that load following and frequency control requirements can increase for significant penetrations of wind plants on a utility system [2,5,20,21]. Penetration levels that are significant are correlated to the type and size of the generation mix and the wind resource. A primary application of wind power generation is expected to be large arrays of megawatt size WTs connected to the utility bulk transmission network. While large arrays are more economical than dispersed wind turbines, array output power variations due to weather fronts can cause excessive frequency excursions. To limit frequency and area control error deviations, one study has recommended that the rated WT array capacity should be limited to a few percent of the utility's system capacity [21]. In another study, it was found that minute-to-minute ramping and daily frequency excursion limits may require WT operating restrictions and/or increased spinning reserve [2].

The impact of intermittent generation on load following and spinning reserve requirements have been studied by several investigators [1,5,20,21]. One study [20] indicated that spinning reserve and load following requirements increased almost linearly with respect to penetration of intermittent generation for the utility that was examined. Increased spinning reserve requirements for significant penetration levels have been suggested from other studies as well [1,5,21]. As spinning reserve and load following requirements increase, the economic benefits of wind electric generation per rated capacity decreases. This is due to the cost penalties associated with reductions in conventional generation unit efficiencies. All of these studies treat wind generation as negative load.

#### SUMMARY

A review of issues and concerns of the electric utility industry for the integration of wind electric generation has been performed. These issues have been classified as planning, dynamics, and operations. Selected studies in each of these areas have been discussed.

The discussion focuses on generation and transmission planning since the WT applications have been limited to bulk system inertia. A difficulty in performing planning studies for wind electric generation is the lack of utility acquired data on installation and operation costs from non-research oriented activities. Utility experience with WTs in the near future and improvements in wind forecasting methods will reduce these uncertainties.

Dynamic analysis of WT arrays interacting with utility systems and individual WT interaction have not revealed any serious problems. Studies in this area are continuing.

Operational impacts of WT arrays could be significant if penetration levels are not carefully coordinated with system response and dispatch requirements. The variable nature of wind could cause present spinning reserve and load following practices to be inadequate to meet traditional utility operating guidelines. Further research is required to

identify critical parameters which are needed to establish the relationship between the dispatch, control, and operation of WTs and utility systems.

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## ECONOMICS OF WIND ENERGY FOR UTILITIES

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As the cost of generating electricity by what has heretofore been considered conventional means continues to climb sharply, the nation has been looking toward alternative methods to produce electricity. Wind energy conversion is among the alternatives being considered.

Utility acceptance of this technology will be contingent upon the establishment of both its technical and economic feasibility. This paper presents preliminary results from a study currently underway to establish the economic value of central station wind energy to certain utility systems. The results for the various utilities are compared specifically in terms of three parameters which have a major influence on the economic value: a) wind resource, b) mix of conventional generation sources, and c) specific utility financial parameters including projected fuel costs.

For the study the economic value is derived from the total savings created as a result of reducing the need for conventional generation by making available energy that is generated by wind turbines. The results presented in this paper, however, are only for fuel savings and do not reflect any savings resulting from deferred or displaced conventional capacity.

The wind energy is derived from modeling either MOD-2 or MOD-OA wind turbines in wind resources determined by a year of data obtained from the DOE supported meteorological towers with a two-minute sampling frequency. In this paper, preliminary results for six of the utilities studied are presented and compared.

## INTRODUCTION

In early 1976 the Energy Research and Development Administration (ERDA), subsequently integrated in the Department of Energy (DOE), issued a Request for Proposal (RFP) entitled "Candidate Sites for Installation and Field Testing of Large Experimental Wind Turbine Systems". ERDA solicited proposals from electric utility systems only and the response to the RFP resulted in the selection of 17 candidate sites. At these sites, where no meteorological towers existed, DOE provided funds to place towers and institute data collection in accordance with standards established by DOE.

In early 1979 DOE initiated a program to estimate the economic value of wind energy conversion systems (WECS) to the utility systems providing these sites. JBF Scientific Corporation was contracted by the Solar Energy Research Institute (SERI) to determine this economic value for the host utilities at nine of these sites and a tenth utility using the wind resource from one of the nine sites. Table 1 contains a list of the utilities for which the economic value of wind energy was determined and indicates, as well, the candidate site from which the wind resource data was obtained.

Table 1. Utilities For Which the Economic Value of Wind Systems Is Being Determined

UTILITY	SITE
BLOCK ISLAND POWER CO.	BLOCK ISLAND
CLAYTON MUNICIPAL ELECTRIC SYSTEM	CLAYTON
CONSUMERS POWER COMPANY	LUDINGTON
HAWAIIAN ELECTRIC COMPANY	KAENA POINT.
HOLYOKE GAS AND ELECTRIC DEPT.	HOLYOKE
LOS ANGELES DEPT. OF WATER & POWER	SAN GORGONIO
PACIFIC GAS AND ELECTRIC COMPANY	POINT ARENA
PUERTO RICO ELECTRIC POWER AUTHORITY	CULEBRA
SOUTHERN CALIFORNIA EDISON CO.	SAN GORGONIO
SOUTHWEST PUBLIC SERVICE CO.	AMARILLO

JBF 1968

For this study the economic value of the wind energy is defined as being the total savings in costs derived from the displacement of conventionally generated energy by the wind generated energy. These savings come from fuel and other incremental costs, operating and maintenance costs, and the carrying costs of deferred or displaced conventional capacity. There may be other costs incurred in order to maintain proper operation of the utility system as a result of incorporating wind energy into the generation mix; these were not considered in this study.

These savings that result from the displaced energy were calculated utilizing techniques that the utility industry has developed to determine the relative economic attractiveness of alternative generation expansion plans.

The differences between the industry developed approach and the approach used in this study relate to three specific factors which make electric energy derived from wind unlike any of the other electric energy sources traditionally evaluated in utility generation expansion planning. The first of these factors is the stochastic

nature of the wind and the power it produces. Traditional energy sources are dispatchable. They produce power when called upon to do so within the limits of forced outages which occur on a relatively infrequent basis. Wind systems, although dispatchable up to the limit of what they are capable of producing from moment to moment, have a capacity which fluctuates as the wind fluctuates. Their capability can go from no output to the rated capacity of the unit within a relatively few minutes. Fortunately, as their incremental costs are essentially zero, wind systems are among the first units to be dispatched in an economic dispatch and, therefore, whatever energy they can produce will be accepted by the utility system. Consequently, it has been possible to adapt the methodology developed by the electric utility to accommodate a source with rapid and uncontrollable fluctuations in output.

The second factor is the wind system's dependence upon the local wind resource. The wind resource only a short distance away from a selected site could contain a substantially different amount of energy. This site dependency precludes the use of generic characteristics as input to the evaluation process and necessitates that a specific wind system be simulated operating in a specific wind resource and the resulting performance be evaluated in the generation expansion analysis.

The third factor which sets central station wind systems apart from traditional generating sources is the lack of meaningful information as to the projected purchase cost of such wind systems from their manufacturers. This factor, when combined with the previously mentioned observation that wind systems have essentially a zero incremental cost, makes it useful to adapt the traditional process to solve for the economic value of the wind system rather than assuming an estimated price.

The approach applied in this study for determining the value of wind generated electricity does follow the accepted utility practice for evaluating generation expansion alternatives with some modifications made to accommodate the three above-mentioned factors. Two general categories of input data are required to calculate the value of wind energy. The first category consists of data related to the wind system, its installation, and performance. The second consists of data related to the specific utility under investigation.

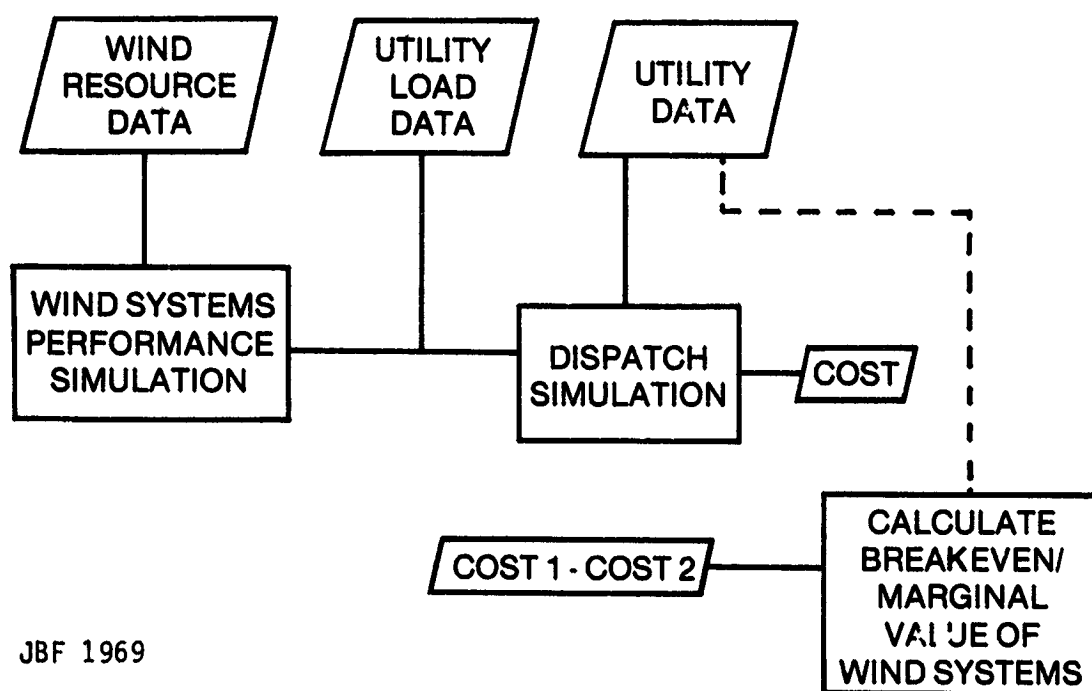
This paper presents some preliminary results from the study for several of the utilities. These results are for savings in incremental, and operating and maintenance costs only. No consideration of deferred or displaced capacity is included in this paper except in describing the methods used in determining the total value of wind turbine systems.

The primary emphasis of this paper is to compare the results from the various utilities with respect to three factors which influence the economic value of wind systems to those utilities. These factors are the amount of wind energy produced by the specific wind turbine in

the specific resource, the mix of conventional generation used by the utility to cover its load, and the pertinent economic parameters for that utility including items such as fixed charge rates and fuel costs projections.

#### METHOD FOR DETERMINING ECONOMIC VALUE

Figure 1 presents an overview of the approach that was utilized for determining the economic value of wind systems to an electric utility. The process contains three basic segments.



JB F 1969

Figure 1. Method for Determining Economic Value of Wind Systems to Utilities

The first segment processes the wind resource with the wind system performance characteristics to develop the expected hourly wind derived energy. This segment relates to the first of the factors described in the introduction which differentiate this process from the conventional utility process. An input to this process is the wind resource data obtained from the DOE meteorological tower at the particular utility site. The other major input to this segment is the performance characteristics of the wind system under consideration. The output of this segment is the expected wind system energy on an hourly basis. This time correlated energy with its associated zero incremental cost is passed into the generation expansion segment to be dispatched on a first priority basis against the expected utility load.

The generation expansion assessment is made in the next segment of this economic approach. This is the most comprehensive segment with substantial amounts of input required. The principal processes in this segment are the simulation of the economic dispatch operation of the utility system and the analysis of the utility system's reliability.

As electric consumption continues to grow, utility organizations continue to face the problem of adding sources of generation in order to meet their obligations of covering these increasing loads. A major objective in their generation expansion program is to provide energy at the lowest possible cost consistent with established levels of reliability. Not all generation alternatives have the same costs or even cost structures. Substantial variations exist in the relationship between fixed and variable costs over the range of alternative generating sources. Fixed costs are incurred just by the ownership of generation and are present regardless of the energy produced by such generation. Incremental costs, on the other hand, are those costs specifically related to producing energy and are, therefore, a function of the amount of energy produced. As a general rule, generating units that have low incremental costs, which makes them economically attractive for long hours of use, have higher fixed costs. These higher fixed costs are the result of capital investments made to achieve greater efficiency from less expensive fuels. Once a utility acquires a certain set of units to provide generation, such a set is loaded in increasing economic order by incremental cost. This process yields the lowest total cost of generation to the utility.

In order to select which equipment should be added to the mix of generation currently operated by the utility, the equipment mix which would reliably satisfy a projected load profile at the lowest total cost of generation must be identified.

The total cost of generation for a given equipment mix serving a given load profile is the sum of the fixed costs of the equipment involved and the total incremental cost that would be incurred in satisfying the load requirements. The fixed costs relate to the annual cost of carrying the investment in the generation. Incremental costs have to be calculated by simulating the dispatch of generating equipment to satisfy the projected load requirements. The electric utility industry has developed numerous computer models to perform this simulation with varying degrees of sophistication.

The approach for evaluating wind systems as part of an expanding mix of generation equipment utilized one of these models to simulate generation dispatch but includes additional functions to address the three factors which differentiate wind sources from traditional sources.

The major inputs to this segment were the projected utility hourly load data, utility generation data, as well as the hourly energy output from the wind system. The processes of this segment were used numerous times in order to determine the effect varying system condi-

tions will have on the utility operation. An initial base case was run utilizing the hourly utility loads and the generating sources as projected without including any wind source. This established the base costs from which savings were computed as well as the system reliability which serves as a target from which to develop capacity credit.

Subsequent cases were then run with various sets of conventional generation sources which can provide the target reliability. The inclusion of wind generation in the utility equipment mix will improve a utility system's reliability. Consequently, the utility can reduce its capacity of conventional sources and still maintain its target reliability. This reduction in the conventional installed capacity that must be maintained by a utility results in a capacity cost savings that can be directly related to the inclusion of WECS into the utility's equipment mix.

The output of this segment was a series of single-year production and related capacity cost savings for various penetration levels of wind. Although capacity credit was computed in the study, capacity credit results are not included in this paper.

The third segment develops the life-cycle economic value of a wind system to a utility from the calculated single-year cost savings. Other inputs necessary for the value analysis include the various utility financial and economic parameters. The initial step in this process was to develop annual wind system generated savings for each year over the projected life of the wind system. These savings are developed from the computed single year savings using the utility's projected economic parameters. From these the accumulated present worth of the annual WECS generated savings for each year over the projected life of the wind system was calculated. Again, with the use of the utility financial and economic parameters, these accumulated savings are converted into an equivalent first-year investment. This investment represents the maximum investment that could be put into the wind system without adversely impacting the utility economically. This equivalent investment is also referred to as the economic value of the wind system to the utility. This value decreases as the level of WECS penetration into the utility system increases. Comparison of the values of each successive WECS unit installed with the WECS manufacturer's price schedule would determine the economic viability of the wind systems.

In this study the analysis was done for three years, an early 1980 year, 1985, and 1995. The selection of the early 1980's year was based upon the availability of appropriate data. Additionally, the analyses was done for various penetrations of wind systems. Penetration is defined as the percent that the wind energy system capacity is of the utility system peak demand. Penetrations of 5 and 10 percent were analyzed in each year along with a penetration of 2.5 percent in the first year.

## ANALYSIS RESULTS

This paper presents some preliminary analysis results for six of the electric utilities being studied. They range from a small isolated municipal system to large interconnected investor-owned systems. Table 2 presents a list of the utilities as well as indicates the utility abbreviations used on the graphs upon which the results are presented.

Table 2. Utilities for Which Preliminary Results are Presented

UTILITY	ABBREVIATION
CLAYTON MUNICIPAL ELECTRIC SYSTEM CONSUMERS POWER COMPANY LOS ANGELES DEPT. OF WATER & POWER PACIFIC GAS AND ELECTRIC COMPANY PUERTO RICO ELECTRIC POWER AUTHORITY SOUTHERN CALIFORNIA EDISON CO.	CMES CPC LADWP PG & E PREPA SCE

JBF 1981

The amount of wind energy available to each of the utilities is determined by simulating the performance of a wind turbine in the appropriate wind resource. The matching of the wind sites with the utilities was provided in the introduction. A year of two-minute wind data was extrapolated to the hub height of the wind turbine and processed through an input-output curve for the specific wind turbine to develop the power every two minutes. These were combined to produce the hourly power to be compatible with normal utility power data.

Two of the ten utilities that are the subject of this study, including one for which results are presented in this paper, are small isolated utility systems. Both these system are too small to be able to incorporate MOD-2 wind turbines into their generation mix without exceeding the penetration levels for wind energy that were established for this study. Coincidentally, both of these utilities are participants in the DOE large wind turbine programs and have MOD-OA wind turbines. For these reasons, MOD-OA wind turbine performance was simulated in each of these utilities to develop the amount of wind energy available to each of these utilities. Figure 2 shows both the average wind speed calculated from the data obtained at that site for 1979 and the capacity factor for the MOD-OA wind turbine operating in that resource. Of the two locations, Block Island, Rhode Island has a slightly better average wind speed and a significantly better capacity factor.



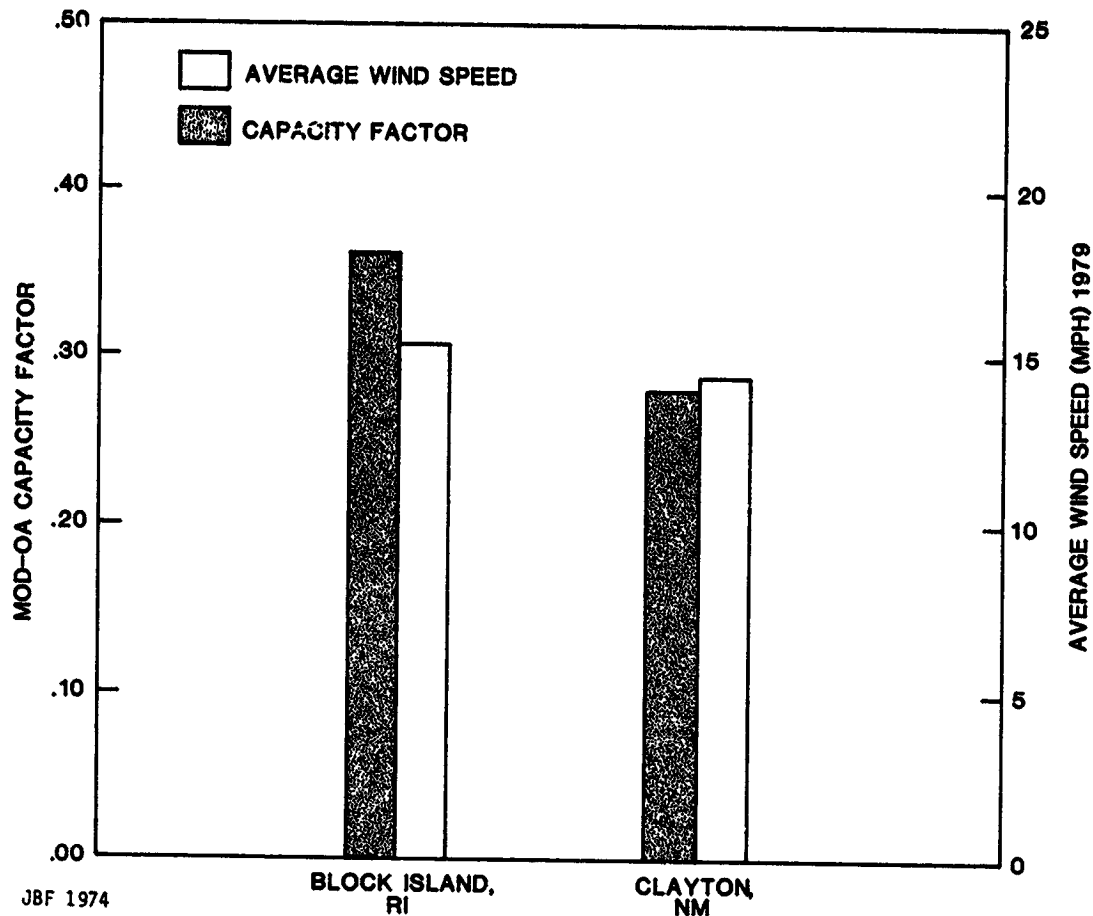


Figure 2. Wind Speed and MOD-OA Wind Turbine Performance

The MOD-2 machine is simulated in the appropriate wind resource to determine the energy available to each of the other utilities.

As the analysis for both Southern California Edison Company and Los Angeles Department of Water and Power used the San Geronio resource, only four sets of results are presented in Figure 3. Of the six sites presented, the poorest average wind speed was at Clayton, New Mexico whereas the poorest capacity factor was for the MOD-2 at Point Arena, California.

A significant part of the characterization of a utility for the purpose of establishing the economic value of wind energy includes a description of the mix of generating sources by fuel type and efficiency.

The mix of generating sources for a given utility is a reflection of size, regional fuel supply consideration, the financial structure, and load of the utility. These mixes have evolved over the years based upon a series of generation expansion evaluation efforts to identify the least costly means of producing energy to supply the utility load.

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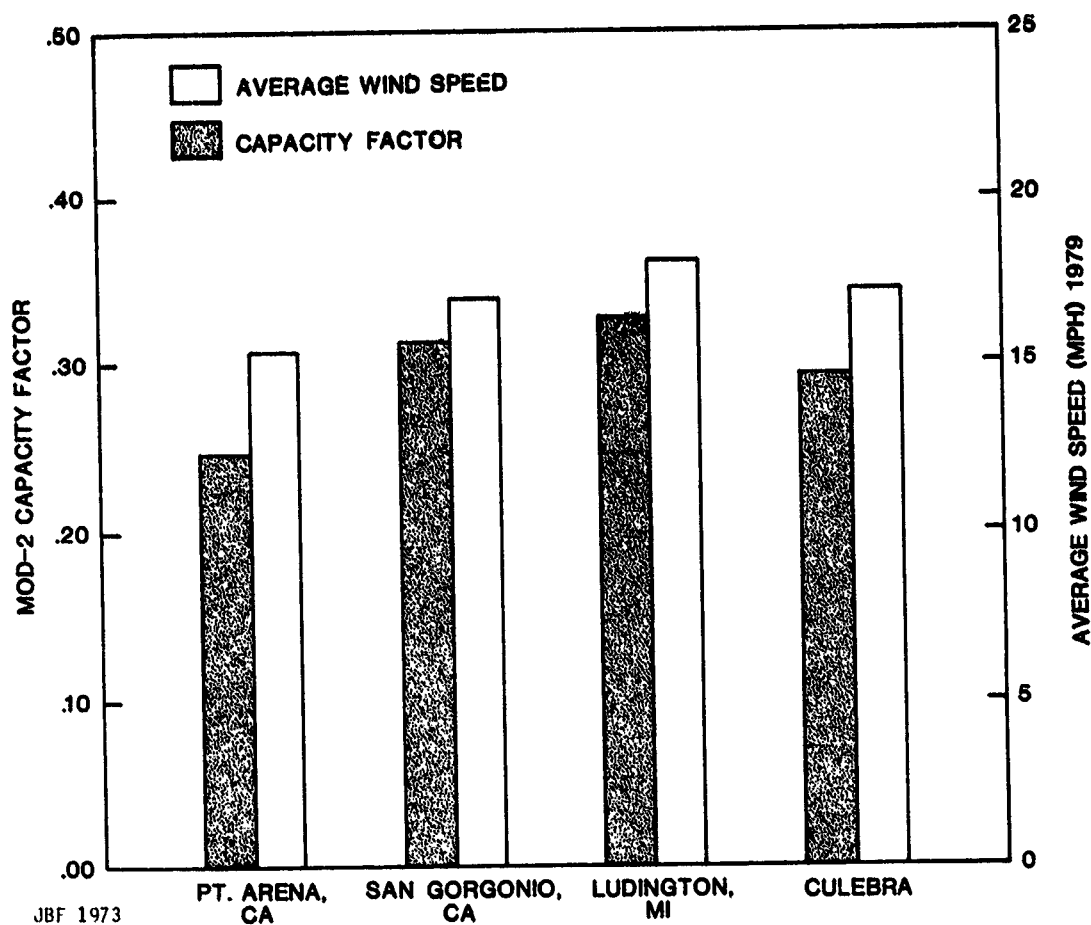


Figure 3. Wind Speed and MOD-2 Wind Turbine Performance

The next three graphs present comparisons which directly relate to generation mix impact upon the derivation of the value of wind systems to the utility. They are the utility capacity projections for each of the years of analysis by fuel type, the generation projected from that capacity for 1985, and finally, the generation displaced by the wind systems for 1985 for both the 5 percent and 10 percent penetration levels.

Figure 4 contains the capacity projections for each of the six utilities. The relative mix by fuel type, the change in this mix, and the relative growth in installed capacity can be seen from this graph.

The capacity is economically dispatched to meet the utility load. It is therefore useful to show the projected generation by fuel type. Figure 5 provides this breakdown for each of the six utilities as projected for 1985.

The hourly dispatch of generation combined with the hourly displacement of energy by the wind systems result in a displacement of fuel by wind energy. The breakdown of this displacement by fuel type for the six utilities is shown in Figure 6. This clearly shows that

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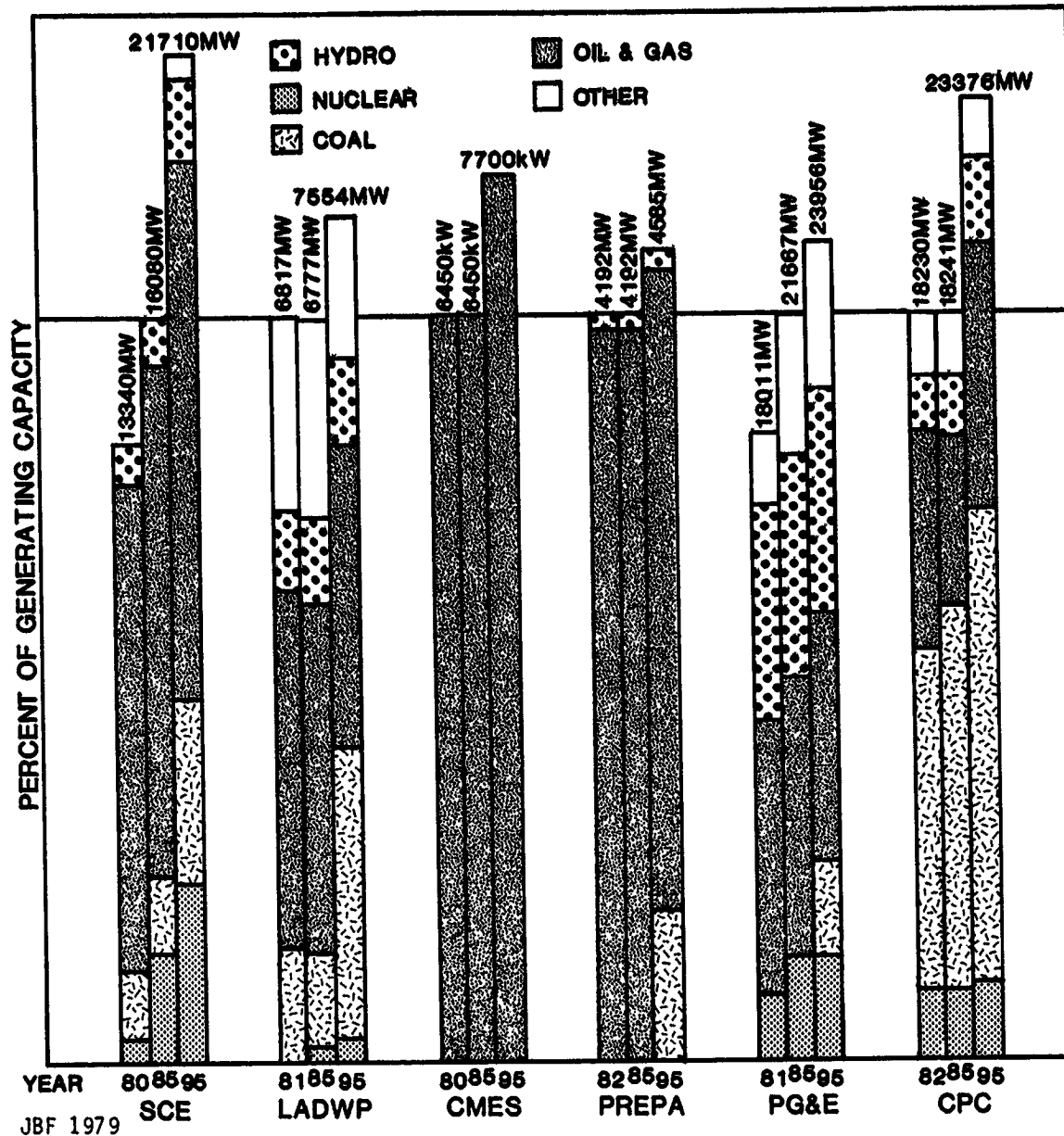


Figure 4. Utility Capacity Projections

except for Consumers Power Company, which has little oil generation, essentially all the value for wind energy from these utilities is derived from displacing oil.

Conversion of the displaced fuel into dollars and dividing by the installed capacity of wind systems for each penetration and utility provides a useful comparison among the utilities. These results are shown in Figure 7. On this graph the annual savings range from under \$100 per kW for Consumers Power Company with its lower cost fuels to a savings in excess of \$260 per kW for Southern California Edison Company with its 100% oil displacement.

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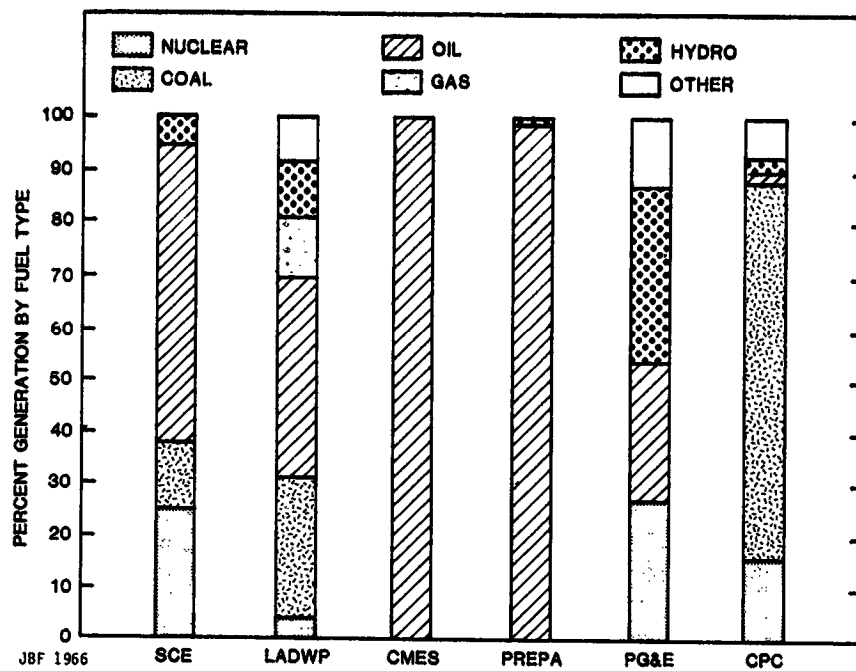


Figure 5. Projected Utility Generation by Fuel Type for 1985

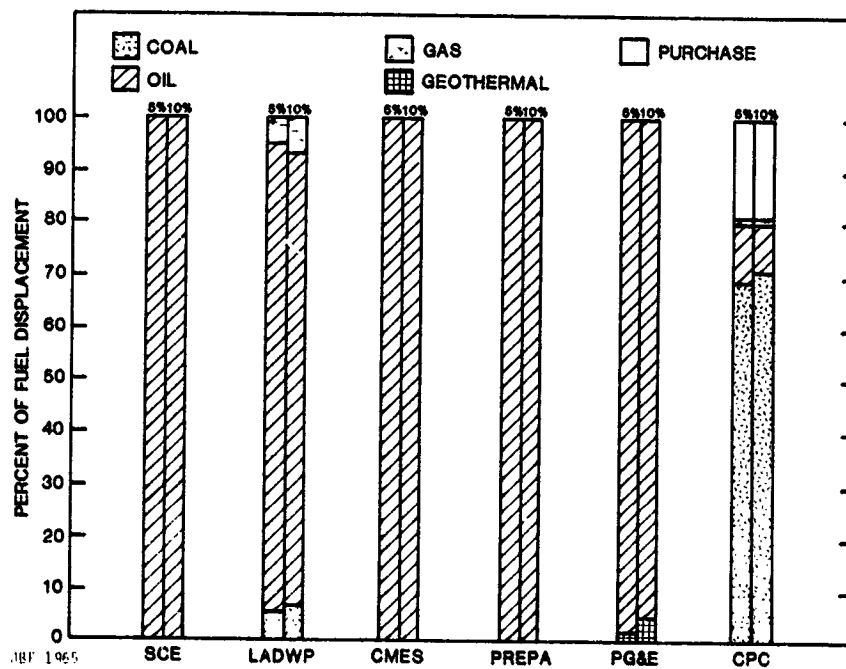


Figure 6. Projected Utility Fuel Displacement by Wind Systems for 1985

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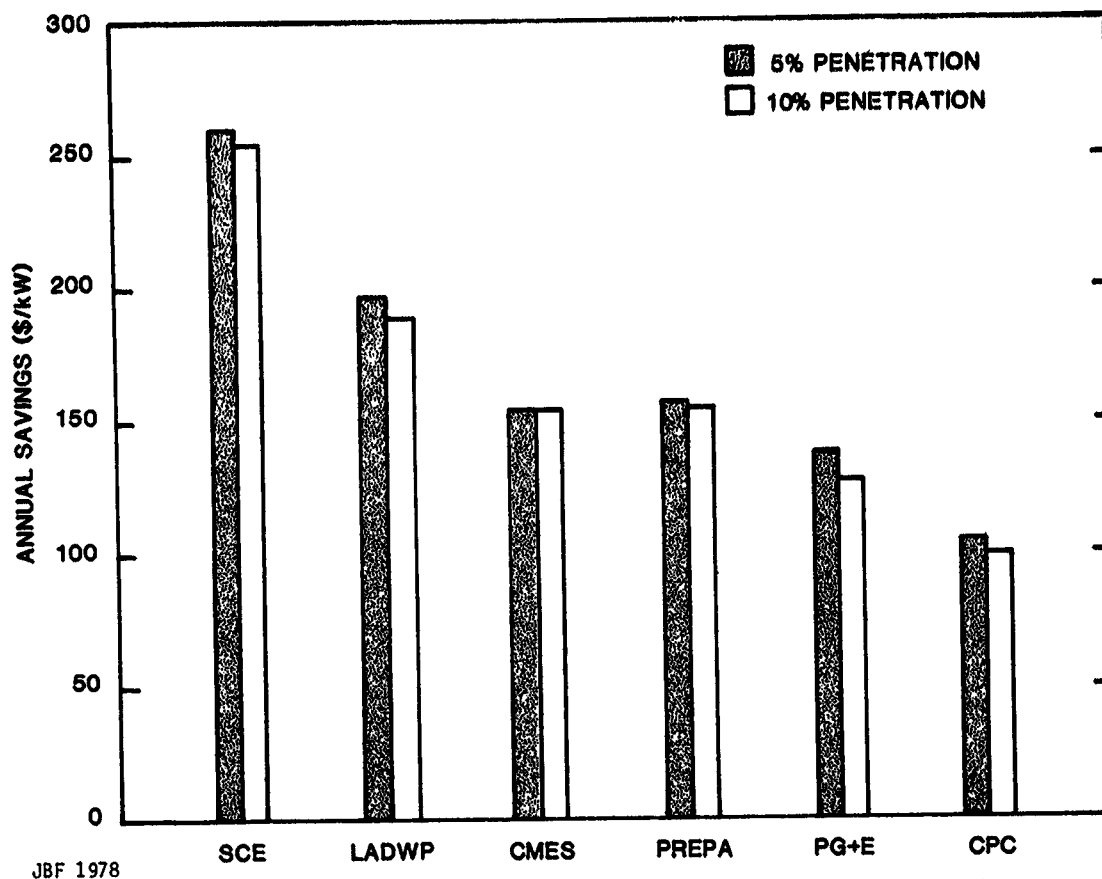


Figure 7. Projected Annual Utility Savings for 1985

In the section in which the method for determining economic value was discussed, it was pointed out that the value is determined by extrapolating the annual savings for the first year to an annual savings for each year of the life and, by the use of normal present worth techniques, converting them to an equivalent first year investment. This investment is equal to the value of the wind system. This process involves a series of calculations utilizing certain economic parameters relative to the particular utility and reflective of its financial structure and its projections of the future economic climate. A composite economic parameter which is used in these computations is the fixed charge rate. The fixed charge rate is essentially the projected equivalent uniform annual carrying costs of a similar plant investment made by that utility divided by the initial cost of the investment. Figure 8 is a graphical presentation of the fixed charge rates for each of the utilities in order of increasing rates. As might be expected, the two municipally owned utilities exhibit the lowest rates which is consistent with their ability to raise capital through borrowing at lower interest rates. Investor-owned utility systems must divide their capital requirements between borrowing and the higher cost process of issuing additional equity.

Indicative of these economic parameters, including the utility financial structure and fuel escalation rate projections and their use in

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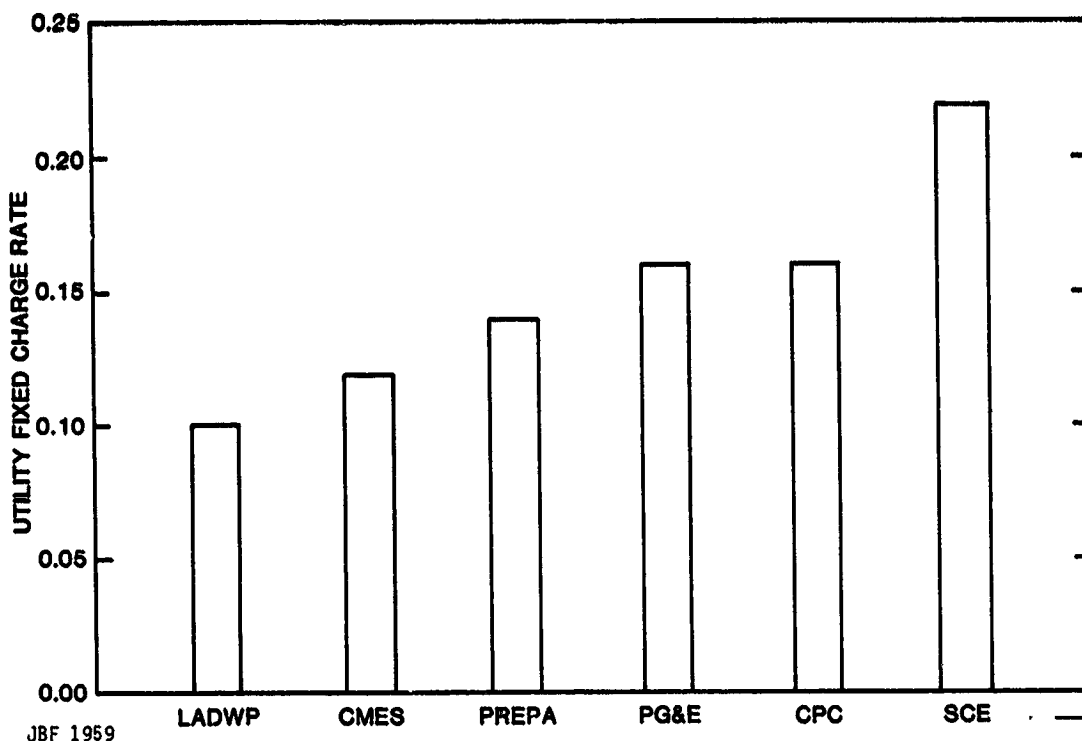


Figure 8. Utility Fixed Charge Rates

this process to determine the economic value of wind systems to a utility, is the value to savings ratio. The value to savings ratios are provided in Figure 9 in the same sequence as were the fixed charge rates. The inverse relationship does not hold true primarily due to the impact on the value determination of fuel escalation rates as used by the utility. Figure 10 provides a representative period of average annual fuel escalation rates by fuel type. It must be remembered that, with the exception of Consumers Power Company, most of the savings were produced by displacing oil generation, hence a comparison of the oil price escalation projections is most significant. Based upon the fixed charge rates alone, it could be expected that Southern California Edison would have the lowest value to savings ratio, and indeed that is the case. However, by similar logic one might expect that the Los Angeles Department of Water and Power would have the highest value to savings ratio, and that is not the case. A review of both their projected oil escalation rate and the Clayton Municipal Electric System projected oil escalation rate shows why they did not have the highest value to savings ratio.

Earlier it was indicated that three factors influence the economic value of wind systems to utilities. In the preceding paragraphs a comparison among the six utilities for each of the three factors has been presented. These factors combine to provide the economic value of wind system to the utilities. In Figure 11 the marginal value of wind systems for each of the utilities for 1985 is presented. Marginal value is defined as the value derived from adding one addition-

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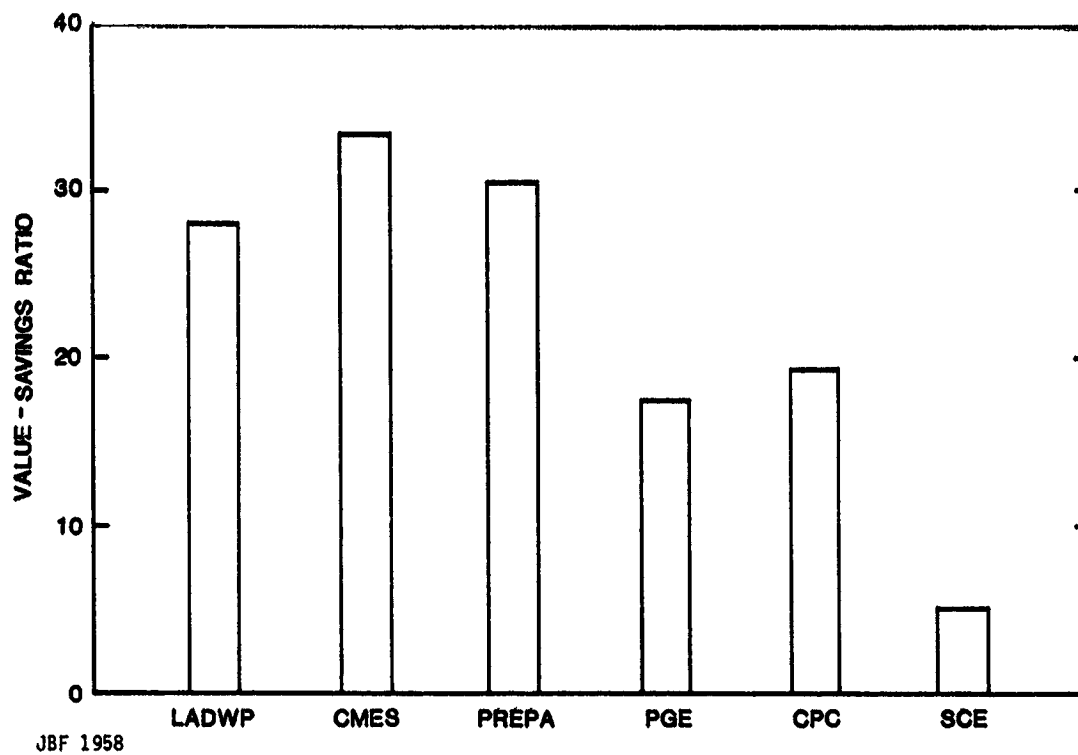


Figure 9. Utility Value to Savings Ratios

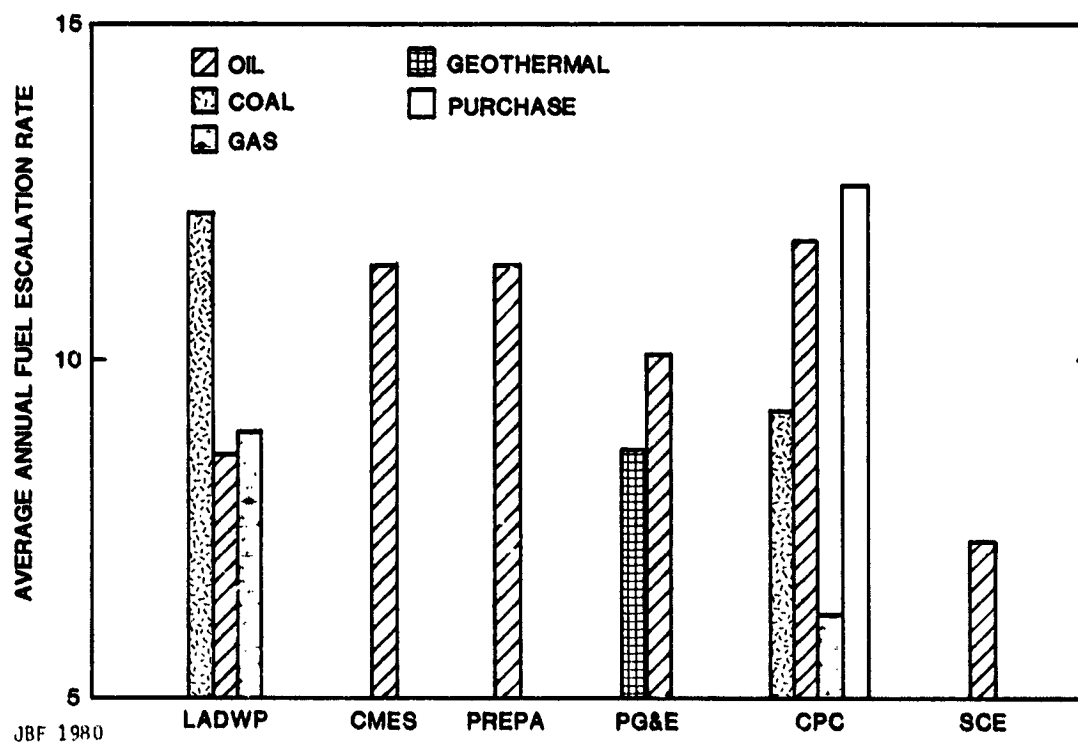


Figure 10. Average Annual Utility Fuel Escalation Rates from 1985 to 1995

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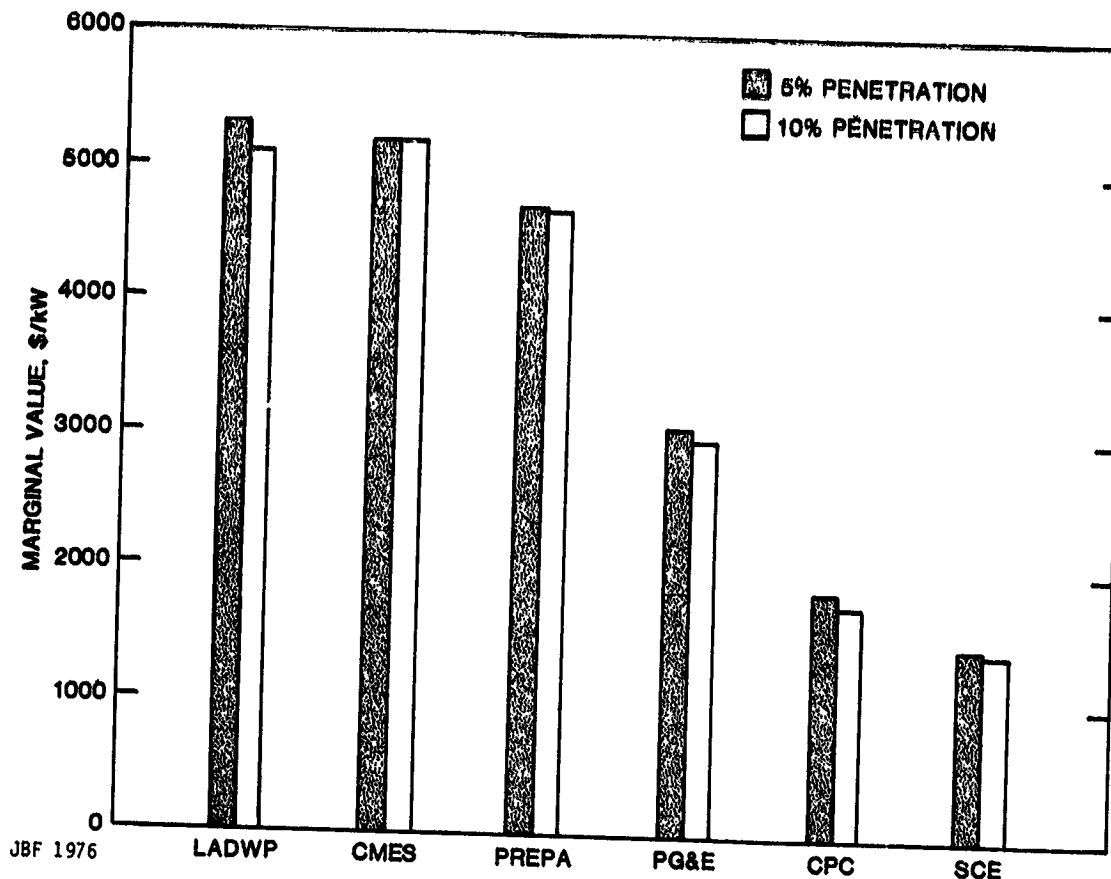


Figure 11. Marginal Value of Wind Systems for 1985

al wind unit to the penetration level for which it is expressed. The marginal value is provided for both the 5 and 10 percent penetration levels for 1985. These marginal values range from a high of over \$5200 per kW for the Los Angeles Department of Water and Power at the 5 percent penetration level to a low of almost \$1400 per kW for its neighboring utility system, Southern California Edison Company at the 10% penetration level.

Although both extremes present good values for wind systems, they provide an interesting case inasmuch as the analysis for each utilized the wind data from the San Geronio site and a simulation of the MOD-2 wind turbine, hence neither the wind resource nor the wind turbine contributed to the difference.

Figure 12 presents the marginal value of wind systems at the 5 percent penetration level for each utility for each of the three projected years of installation. The contribution of each of the three factors has been presented in the previous material for 1985. The analysis performed in the study provided the results seen in Figure 12. Not only have the marginal values changed for 1995 installations, but the different rates at which they have changed results in a different ranking among the six utilities for 1995.



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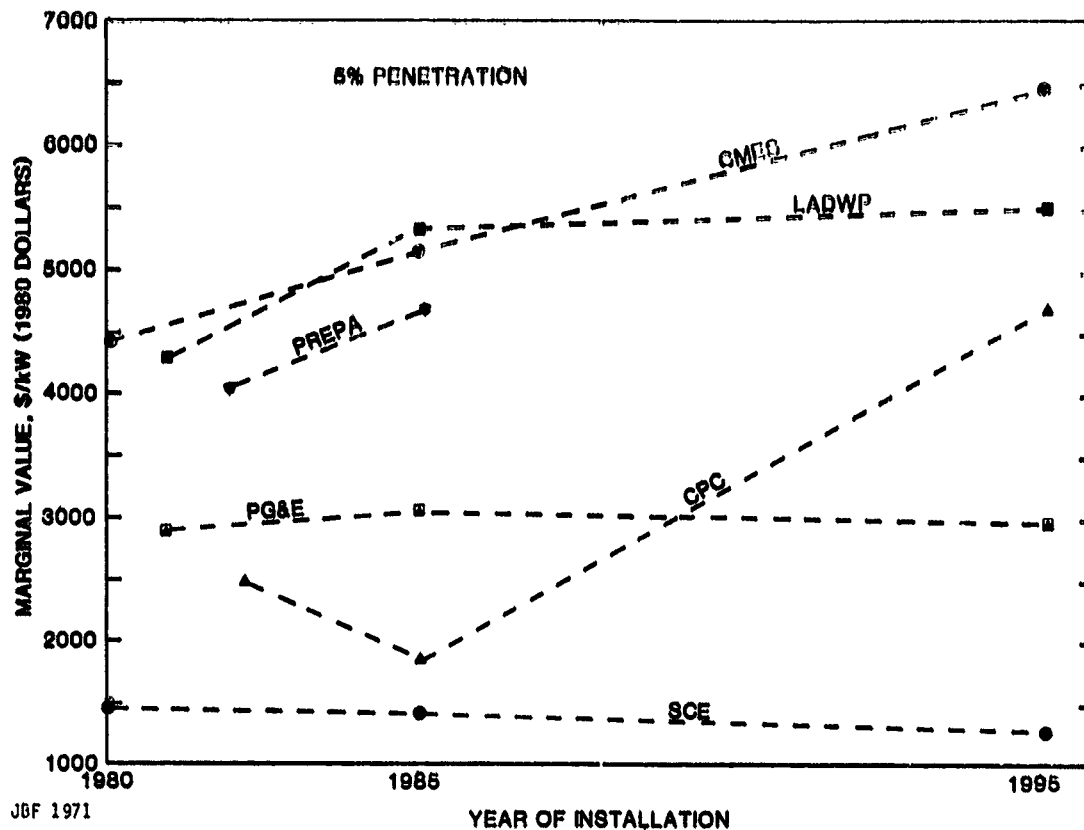


Figure 12. Marginal Value of Wind Systems  
vs. Year of Installation

There are several observations worthy of note that can be made relative to these results. It is normally expected that the economic value of wind systems to the utility will increase over time. The results for Southern California Edison run contrary to that expectation. Two factors that we have previously discussed explain this result. Southern California Edison is shifting away from oil in its projected generation mix and, therefore, some of the displacement in later years may be of fuels other than oil. Secondly, the fuel escalation rates that they provided were the lowest of the six utilities. The results for Consumers Power Company show a drop in value from 1982 to 1985 and then a substantial increase in value to 1995. The drop from 1982 to 1985 reflects an increase in the amount of coal generation displacement whereas the 1995 results reflect displacement of peaking oil units.

This paper has presented some of the preliminary results on the economics of wind energy for certain utilities. In addition, it has attempted to provide some insight into those factors which can contribute to the value of the wind systems to the utilities.

QUESTIONS AND ANSWERS

M. Goldenblatt

From: F. March

Q: Did you consider a capacity credit related to: 1) replacement of retired equipment, 2) the intrinsic value of improved reliability (i.e., avoidance of revenue loss)? How would your propose to take these factors into account?

A: *Retiring equipment was not taken into account in the study. Capacity credit was calculated by identifying the effect wind turbine generation had on LOLP and deferring future additions no longer needed as a result of adding wind turbines to a utility's equipment mix.*

From: W. Vachon

Q: Did Clayton change their fuel use? They used to start their diesels with oil and switch to natural gas to save money.

A: *Clayton's fuel usage is dual fuel. The figure only showed the dominant fuel.*

From: R. Hughes

Q: When you say "Fuel Price Escalation Rate," do you mean absolute price increase or price increase relative to inflation? Are you sure SCE and the other utilities were reporting the same type of escalation rates? Why did you not use DOE estimates?

A: *The price increases for fuel costs were absolute. SCE had a sharp increase before 1985 and a very low one thereafter for its fuel prices. The figure shown was for 1985 and beyond. The study called for using utility estimates for fuel price increase, but it examined the sensitivity of the results to variations in these estimates.*

From: Anonymous

Q: SCE escalation rates imply oil price increases well under 10% per year. Is this realistic?

A: *I cannot answer except to say the numbers used in the study were supplied by the utilities themselves.*

From: W. A. M. Jansen

Q: Were variable operation costs of conventional plants other than fuel taken into consideration?

A: No.

M. Goldenblatt (continued)

From: R. L. Moment

Q: Your charts show SCE to have the lowest economic benefits of the various utilities included. Why do you think they have been so active in wind energy, as evidenced by their taking the lead a few years ago? Perhaps their economic analysis is quite different from yours.

A: *SCE is investigating machines that were not installed as a result of their economic value. SCE is the largest user of oil in the U.S. Their decision to purchase wind turbines was probably based upon a combination of political, institutional, environmental and economic factors. Also, just because SCE had the lowest wind turbine value (of the six utilities studied) did not mean it was a bad economic decision for it to investigate the potential for wind generation.*

From: M. Lotker

Q: Why is PGE's cost of money so much less than SCE's?

A: *The cost of money values used in the study were supplied by the utilities themselves. I do not know why PGE's was less than SCE's.*

From: K. M. Foreman

Q: Could not capacity credit be applied to displace obsolete or totally depreciated equipment for those utilities that anticipate no growth?

A: *Yes. For the study performed, however, that was not considered as an option.*

From: L. Rowley

Q: In 1985 do you see wind turbines displacing oil among the larger utilities -- how many wind turbines will be in service by 1990?

A: *I can only say that in the last 5 years I have seen a significant change in utilities' attitudes towards the potential for wind energy. As to the amount of penetration that might occur in the next decade, I hesitate to even make a guess.*

From: D. Bain

Q: How sensitive is the break-even and marginal value to FCR? Would uniform FCRs reorder the results?

A: *The answers are very sensitive to FCR. Uniform FCRs would reorder the results but would be unrealistic.*

LARGE HORIZONTAL-AXIS WIND TURBINE WORKSHOP

Advanced Wind Turbine Systems

Session Chairman - R. W. Thresher (Oregon State University)

"Conceptual Design of the 6 MW Mod-5A Wind Turbine Generator"

R. S. Barton

W. C. Lucas

(General Electric Company)

"Conceptual Design of the 7 Megawatt Mod-5B Wind Turbine Generator"

R. R. Douglas

(Boeing Engineering & Construction Company)

"Workshop Wrap-Up Report"

R. W. Thresher

(Oregon State University)

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CONCEPTUAL DESIGN OF THE 6 MW  
MOD-5A WIND TURBINE GENERATOR

R. S. Barton - Supv. Engineer, Systems Engineering  
W. C. Lucas - Manager, Wind Projects Engineering

General Electric Company  
Advanced Energy Programs Department  
P. O. Box 8661  
Philadelphia, Pa. 19101

ABSTRACT

The General Electric Company, Advanced Energy Programs Department, is designing under DOE/NASA sponsorship the MOD-5A wind turbine system which must generate electricity for 3.75 ¢/KWH (1980) or less. During the Conceptual Design Phase, completed in March, 1981, the MOD-5A WTG system size and features were established as a result of tradeoff and optimization studies driven by minimizing the system cost of energy (COE). This led to a 400' rotor diameter size.

The MOD-5A system which resulted is defined in this paper along with the operational and environmental factors that drive various portions of the design. Development of weight and cost estimating relationships (WCER's) and their use in optimizing the MOD-5A are discussed. The results of major tradeoff studies are also presented. Subsystem COE contributions for the 100th unit are shown along with the method of computation.

Detailed descriptions of the major subsystems are given, in order that the results of the various trade and optimization studies can be more readily visualized.

PROGRAM SCOPE

The MOD-5A Wind Turbine Generator program is a basic element in the overall Federal Wind Program. The goal of the MOD-5A program is to develop a reliable, commercially viable wind energy system, able to produce electricity at a cost of energy (COE) of 3.75 ¢/KWH or less in 1980 dollars, at a site with a 14 MPH annual average wind speed. The program is sponsored by the DOE, with technical management by the NASA Lewis Research Center. General Electric's Advanced Energy Programs Department is the prime contractor. GE's major subcontractors are Gougeon Brothers (GB) for the wood laminate blade, Philadelphia Gear Corporation (PGC) for the gearbox, and the Chicago Bridge and Iron Company (CBI) for the steel shell tower, foundation and erection.

The program began in July of 1980, and is organized into three design phases: Conceptual Design, which was completed in March, 1981; Preliminary Design, which is now underway; and Final Design, scheduled to begin in March, 1982. Each design phase is culminated by a comprehensive design review which has two main objectives: to conduct an

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in-depth review of the design's technical adequacy, and to verify that the program's COE requirement of 3.75 ¢/KWH or less is still being met. (The methodology for estimating and tracking COE is described later.) As the design work progresses through the various phases, subsequent design reviews focus on successively greater levels of detail. Much emphasis is placed on achieving a simple, reliable and maintainable design. In parallel, development and qualification testing is used to verify new elements of the design.

Fabrication of hardware is scheduled to begin late in 1982, with installation and checkout of the first unit completed early in 1984, followed by a two year Operation and Maintenance phase. There is an option in the contract for the manufacture and installation of two additional units. At this point in time, no sites have yet been identified for the MOD-5A.

The purpose of this paper is to describe the results of the Conceptual Design phase, updated by the work accomplished so far in Preliminary Design. We at GE believe that the MOD-5A design meets the program objectives and offers significant advancement in the state-of-the-art. Thus, it is appropriate to review a summary of the major Conceptual Design Objectives as shown in Figure 1.

OBJECTIVE	ACHIEVEMENT
<ul style="list-style-type: none"> <li>• DEVELOP AN OPTIMIZED LOW COST DESIGN WITH COE LOWER THAN NASA GOAL</li> </ul>	<ul style="list-style-type: none"> <li>• &lt;3.0 ¢/KWH ACHIEVED VS. 3.75¢/KWH GOAL</li> </ul>
<ul style="list-style-type: none"> <li>• VALIDATE THE OPTIMIZATION TECHNIQUE</li> </ul>	<ul style="list-style-type: none"> <li>• POINT DESIGNS VALIDATED WGER'S. SYSTEM OPTIMIZED AT CONCEPTUAL BASELINE DIAMETER 400'</li> </ul>
<ul style="list-style-type: none"> <li>• ADVANCE WIND TURBINE STATE OF THE ART THROUGH INNOVATIVE DESIGN AND OPTIMUM USE OF AVAILABLE OR NEW TECHNOLOGY</li> </ul>	<ul style="list-style-type: none"> <li>• MANY MAJOR INNOVATIONS INCORPORATED IN DESIGN (GEARBOX, BLADE MAT'L ETC)</li> </ul>
<ul style="list-style-type: none"> <li>• VALIDATE THE DESIGN TOOLS</li> </ul>	<ul style="list-style-type: none"> <li>• ANALYTICAL TECHNIQUES AND CODE VALIDATED DURING CONCEPTUAL DESIGN PHASE</li> </ul>
<ul style="list-style-type: none"> <li>• POSITION PROGRAM FOR SMOOTH TRANSITION TO PRELIMINARY DESIGN PHASE</li> </ul>	<ul style="list-style-type: none"> <li>• CONCEPTUAL DESIGN COMPLETED TO POINT WHERE DESIGN SPECS AND PRELIMINARY DESIGN DRAWINGS CAN NOW BE PREPARED</li> </ul>

ALL OBJECTIVES ACHIEVED

FIGURE 1. DESIGN OBJECTIVES

## SYSTEM REQUIREMENTS

### Wind Regime

The MOD-5A system has been developed for a wind regime having a mean wind speed of 14 MPH (at 10 meters). This has influenced the rotor size and rating, Fig. 2. During Preliminary Design, the system is being

examined for other wind regimes. The impact of a lower and higher mean wind speed upon the current MOD-5A is discussed later.

GE has selected the cut-in wind speed to assure maximum output and to pre-empt "false starts" in low winds wherein mechanical and electrical losses are likely to exceed the energy to be derived from the wind. A cut-in wind speed of 14 MPH (at the hub or equivalently 9.5 MPH at 10 meters) has been established. A 25% blade tip length was found necessary for satisfactory startup. The cut-out wind speed was first set at 44 MPH because the additional available energy is insignificant at higher wind speeds. Cut-out was not based on structural limitations and the current MOD-5A design high cut-out is higher.

Low cut-out as shown in Figure 2 is at 11.5 MPH and is based on rotor underspeed. Gear shifting for two speed operation occurs near 20 MPH and rating is reached at 29 MPH.

Cost of energy (COE) is the overriding issue to the successful commercialization of wind turbines. Accordingly, NASA has established the competitive figure of 3.75 ¢/KWH (1980) as a bogey for the MOD-5A WTG program. Projections for the MOD-5A indicate less than 3 ¢/KWH (1980) can be achieved at a 14 MPH wind site.

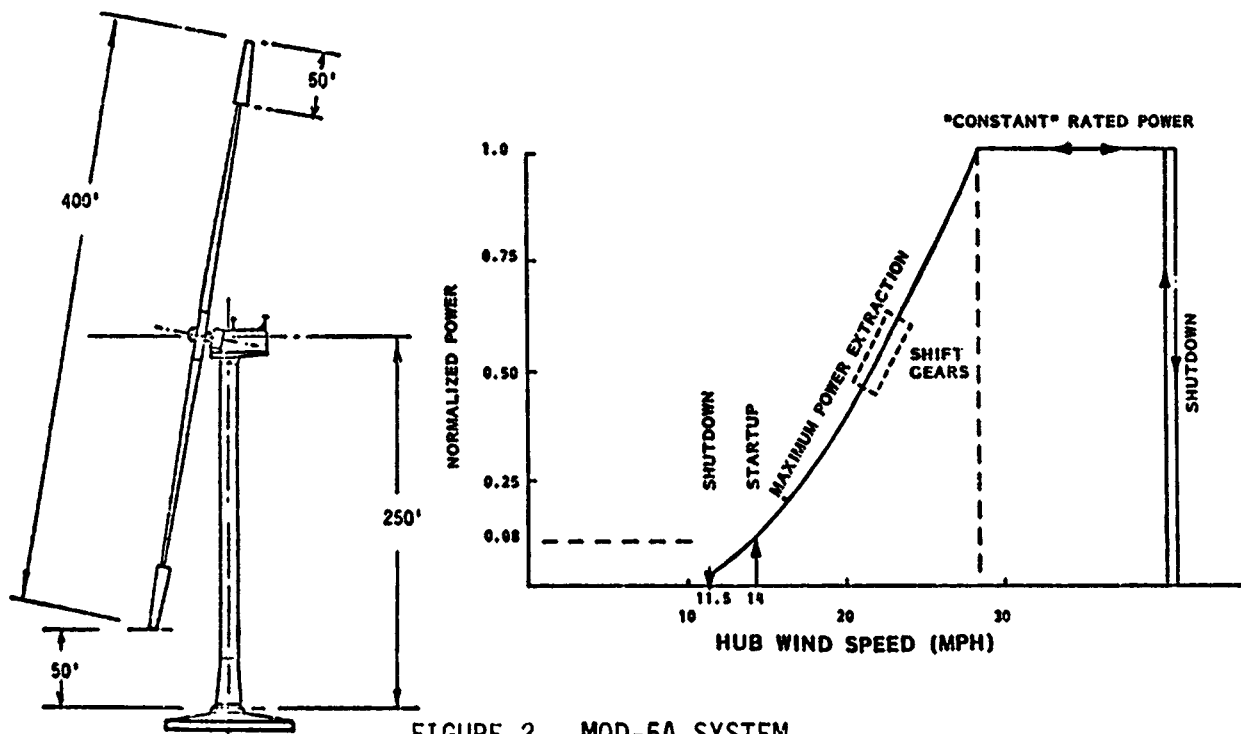


FIGURE 2. MOD-5A SYSTEM

### Design Requirements

Major design requirements and their effect on system design are shown in Figure 3. The MOD-5A is based on a comprehensive design driver analysis and definition.

REQUIREMENT	CRITERIA/VALUE	COMMENTS
COST OF ENERGY	<ul style="list-style-type: none"> <li>• LESS THAN 3.75 ¢/KWH (1980) (SOW)</li> <li>• MINIMIZE</li> </ul>	<ul style="list-style-type: none"> <li>• MAJOR DRIVER IN ALL AREAS</li> </ul>
OPERATIONAL WIND REGIME	<ul style="list-style-type: none"> <li>• 14 MPH MEAN (10 M) (SOW)</li> <li>• CUT-IN AT BELOW 10% OF RATING</li> <li>• CUT-OUT WIND TO MINIMIZE COE</li> </ul>	<ul style="list-style-type: none"> <li>• DRIVER FOR COMBINED TIP SPEED, SPEED RATIO, SOLIDITY TO MINIMIZE COE</li> <li>• DETERMINES TIP LENGTH AND STARTUP 25% TIP, 14 MPH (HUB) ESTABLISHED</li> <li>• DETERMINES SPEED WHERE COE STOPS DECREASING</li> </ul>
AVAILABILITY	<ul style="list-style-type: none"> <li>• 0.92 MINIMUM DESIGN FOR 100TH UNIT BETWEEN CUT-IN AND CUT-OUT (SOW)</li> </ul>	<ul style="list-style-type: none"> <li>• DESIGN GOLAS ESTABLISHED BASED ON RAN ANALYSIS</li> <li>• 0.960+ FOR CLUSTER</li> </ul>
EXTREME WIND	<ul style="list-style-type: none"> <li>• 120 MPH (10 M), 0.1 EXPONENT (SOW)</li> </ul>	<ul style="list-style-type: none"> <li>• DRIVER FOR TOWER AND FOUNDATION</li> <li>• MINIMIZE LOAD BY ORIENTATION</li> </ul>
LIMIT THRUST	<ul style="list-style-type: none"> <li>• 115% SPEED, 1.2 <math>C_L</math> DESIGN POINT WITH 4.6 GUST (GE)</li> </ul>	<ul style="list-style-type: none"> <li>• DRIVING LOAD ON PARTS OF BLADES</li> </ul>
EMERGENCY FEATHER	<ul style="list-style-type: none"> <li>• MAX NEGATIVE <math>C_L</math> ON TIP (-1.5), LOW <math>C_L</math> INBOARD</li> </ul>	<ul style="list-style-type: none"> <li>• NOT AS CRITICAL AS LIMIT THRUST CONDITION</li> </ul>
SEISMIC	<ul style="list-style-type: none"> <li>• ZONE 3-UBC (SOW)</li> </ul>	<ul style="list-style-type: none"> <li>• NOT A DESIGN DRIVER</li> </ul>
CYCLIC LOADS	<ul style="list-style-type: none"> <li>• 30 YEAR LIFE (SOW)</li> <li>• FATIGUE LOAD FACTORS DETERMINED FROM MOD-0A DATA AND GUST MODEL (SOW TURBULENCE)</li> </ul>	<ul style="list-style-type: none"> <li>• 35,000 START, STOP AND GEARSHIFT CYCLES ESTABLISHED FROM HOURLY DATA ANALYSIS</li> <li>• DRIVING LOAD ON PARTS OF BLADES</li> </ul>
FREQUENCY PLACEMENT	<ul style="list-style-type: none"> <li>• AVOID RESONANCES</li> <li>• TOWER BENDING BETWEEN 1.1 AND 1.8P</li> <li>• DRIVETRAIN TORSION BELOW 0.9P AND <math>\geq</math> 25% CRITICAL DAMPING</li> <li>• BLADE CYCLIC MODES AWAY FROM ODO (<math>N \pm .2</math>)P (EXCEPT TEETER)</li> <li>• BLADE COLLECTIVE AND FIXED SYSTEM MODES AWAY FROM EVEN (<math>N \pm .2</math>)P.</li> </ul>	<ul style="list-style-type: none"> <li>• DRIVES BELL SECTION OF TOWER, HIGH RPM AND RPM RATIO TO INCREASE ENERGY CAPTURE</li> <li>• DRIVER FOR GEARBOX STIFFNESS AND ACTIVE (CONTROL SYSTEM) OR PASSIVE DAMPING</li> <li>• PRELIMINARY DESIGN PHASE REQUIREMENTS FOR SYSTEM</li> </ul>

FIGURE 3. DESIGN REQUIREMENTS

### Environmental Factors

Sound, TVI (television interference) and other wind regimes were the major environmental factors analyzed.

Wind turbine sound levels are dominated by the effect of change in blade angle of attack and corresponding lift pressures. The potential for complaints is highest with the rotor located downwind of the tower, as on the experimental MOD-1 system, where the tower wake produces



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sudden large changes in air flow. The frequency of blades cutting a wake at twice per revolution is sub-audible, but the complaint potential has been tied to the energy in the range from 20 to 50 hertz by spectral analysis of measurements and computed predictions in the audible range.

The MOD-5A system expected sound spectra was computed, Figure 4, for both the upwind and downwind rotor locations at various distances from the rotor. As shown, the baseline upwind rotor location produces less sound energy at 800 feet (solid line) than a downwind rotor would produce at 3200 feet. The upwind rotor generally produces computed sound pressure levels only a few dB above ambient sound, and no complaints are expected.

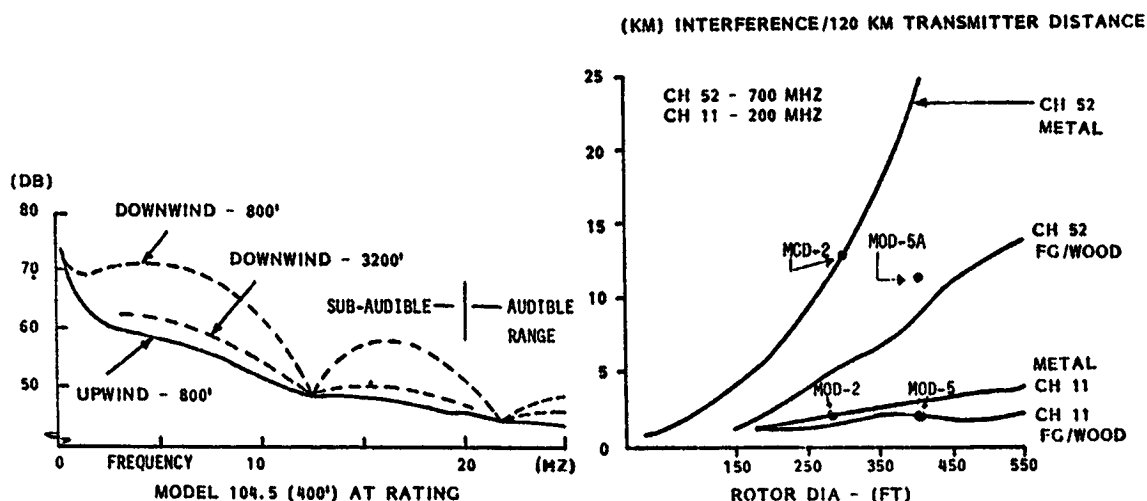


FIGURE 4. SOUND

FIGURE 5. TVI

Wind turbine television interference consists mainly of periodic rotor blade blocking or reflecting of a signal between a television transmitter and home receiver. The interference depends on TV channel frequency such that the higher numbered channels are subject to interference at a greater distance from the wind turbine than lower numbered channels. A metallic rotor provides a better reflector than a non-metallic rotor and causes interference at greater distances. The MOD-5A rotor has wood laminate blades, but lightning conductors and the tip control actuator areas are metallic. An effective reflecting area, 25% of the way from non-metallic to metallic, was conservatively selected as representative. (Figure 5)

The MOD-5A system provides close to optimum performance in a variety of wind regimes. Cost of energy was computed for the baseline Model 204 and for a system optimized for the specific wind regime for three Weibull shaped mean wind speeds and for winds at two sites where wind turbines are being located.

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The MOD-5A is optimum for 14 and 16 MPH regimes. It is within 1.4% of optimum for 12 MPH where a slightly lower power rating is optimum. Model 204 performance at San Geronio and Medicine Bow is within 3% of optimum.

### MAJOR TRADE STUDIES

In developing the Conceptual Design of the MOD-5A WTG, eight major trade-off studies were identified which required specific review and approval by the NASA Project Manager before being implemented. In addition to these eight major trade-off studies, a significant number of other design trade-off studies were performed which led to selection of the baseline configuration. Figure 6 defines the eight major trade-off studies, defines the various design alternatives considered, identifies the selected component or subsystem and also establishes the major attributes of the selected component or subsystem which led to its selection. Some of the studies are discussed in more detail in the following.

STUDY	ALTERNATE CONSIDERED	SELECTION	ATTRIBUTES
1. BLADE MATERIAL	<ul style="list-style-type: none"> <li>• FIBERGLAS (EPOXY &amp; POLYESTER)</li> <li>• STEEL</li> <li>• WOOD EPOXY</li> </ul>	• WOOD EPOXY	<ul style="list-style-type: none"> <li>• LIGHTEST WEIGHT</li> <li>• LOWEST COST</li> </ul>
2. BLADE ARTICULATION	<ul style="list-style-type: none"> <li>• INDEPENDENTLY CONED BLADES</li> <li>• TEETERED ROTOR</li> </ul>	• TEETERED ROTOR	<ul style="list-style-type: none"> <li>• ALLOWS UPWIND</li> <li>• LEAST TECH. RISK</li> <li>• LOWEST COST</li> </ul>
3. WIND ORIENTATION	<ul style="list-style-type: none"> <li>• UPWIND</li> <li>• DOWNWIND</li> </ul>	• UPWIND	<ul style="list-style-type: none"> <li>• LOWEST COST</li> <li>• LOWEST SOUND</li> </ul>
4. TORQUE CONTROL	<ul style="list-style-type: none"> <li>• FLAPS</li> <li>• PARTIAL SPAN CONTROL</li> </ul>	• PARTIAL SPAN CONTROL	<ul style="list-style-type: none"> <li>• LOWEST COST</li> <li>• MOST RELIABLE STARTUP</li> </ul>
5. TOWER HEIGHT	• GROUND CLEARANCE 25' TO 125'	• 50' GROUND CLEARANCE	<ul style="list-style-type: none"> <li>• COST INSENSITIVE 25' TO 75'</li> <li>• CAN MOVE IN EITHER DIRECTION TO ACCOMMODATE OTHER DRIVERS</li> </ul>
6. SYSTEM RPM	<ul style="list-style-type: none"> <li>• ONE SPEED</li> <li>• TWO SPEED MECHANISM (UP TO 2:1)</li> <li>• TWO SPEED ELECTRIC (UP TO 2:1)</li> </ul>	• TWO SPEED MECHANISM 1.3:1 SPEED RATIO	<ul style="list-style-type: none"> <li>• GREATER ENERGY CAPTURE</li> <li>• LOWER COE</li> <li>• SYSTEM FLEXIBILITY</li> </ul>
7. GEARBOX/NACELLE CONFIGURATION	<ul style="list-style-type: none"> <li>• SEPARATE GEARBOX</li> <li>• INTEGRAL GEARBOX</li> <li>• ROTOR INTEGRATED GEARBOX</li> </ul>	• ROTOR INTEGRATED GEARBOX	<ul style="list-style-type: none"> <li>• MOST EFFICIENT SYSTEM</li> <li>• LOWEST WEIGHT</li> <li>• LOWEST COE</li> </ul>
8. ROTOR STOPPING TECHNIQUE	<ul style="list-style-type: none"> <li>• PARTIAL SPAN CONTROL STOPPING</li> <li>• STOPPING BRAKE</li> </ul>	• PARTIAL SPAN CONTROL	<ul style="list-style-type: none"> <li>• SIGNIFICANT STOPPING TORQUE MARGIN</li> <li>• NO NEW HARDWARE FOR THIS FEATURE</li> </ul>

FIGURE 6. MAJOR TRADE STUDIES

### Blade Material Study

Cost of energy, shown in Figure 7 as a function of rotor diameter and power density, optimizes at a 400 ft. diameter system with wood laminate blades operating at 350-375 ft/sec. tip speed. The constant power density curves have shifts due to the gearbox exceeding the constraints needed to ship in one piece. Field assembly and test costs due to large size and weight appear as cost jumps.

Performance is based on a NACA 64-6XX airfoil at 1/4 standard rough. Drag characteristics were conservatively calculated by not including the low drag "bucket" that results from the theoretical performance in the laminar flow region. This airfoil has a reverse curvature on the high pressure trailing edge that can be fabricated more readily with the external mold technique used for wood laminates than with the internal mold technique utilized for filament or tape wound structures.

At the system level, with conservative stress levels, the wood rotor system provided lower COE at less risk than either fiberglass or steel bladed rotors. Further optimization during Preliminary Design has made the rotor even lighter and more efficient.

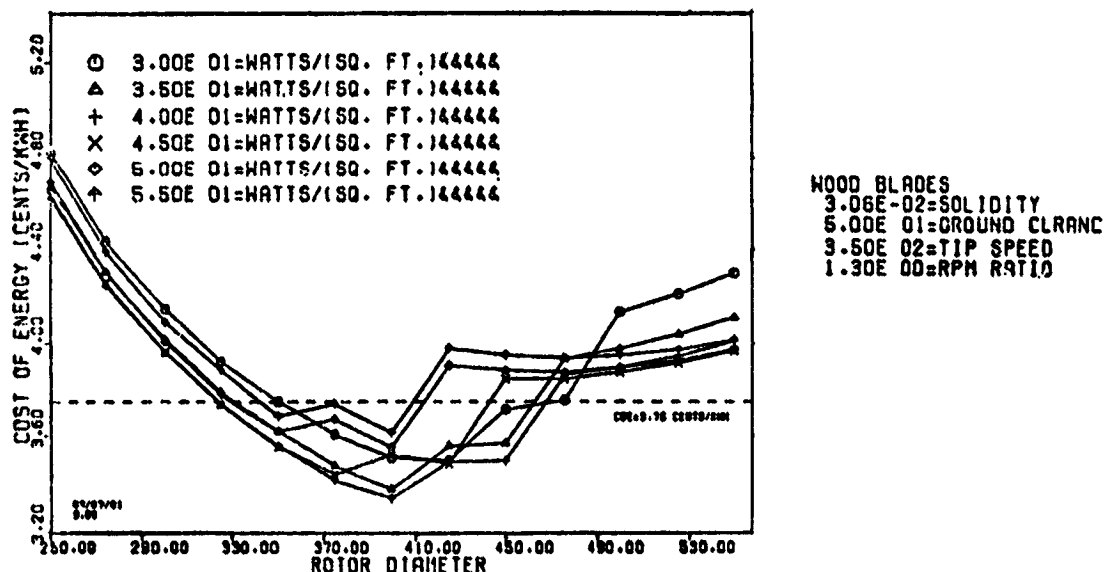


FIGURE 7. BLADE MATERIAL STUDY

### Independent Coning Study

Substantially reduced rotor loads on the independently coned configuration resulted in a 30% savings in rotor weight. On the other hand, approximately a 2% loss in energy capture was encountered due to coning. The cost savings were not quite enough to overcome this energy loss, although the final COE was within 1/2% of the baseline. Additional reasons for retaining the baseline are: 1) Sound is significantly higher with the downwind (due to clearance considerations) independently

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coned system, 2) Lower programmatic technical risk exists with the baseline because it has been extensively analyzed in recent wind turbine programs, and 3) The independently coned hub is considerably more costly due to double hinges, flap restraints, etc.

### Flap Study

The flap concept was developed as shown in Figure 8 with 5 actuators mounted externally to the blade surface driving 10 flap sections in pairs. The trade-off was performed on a relatively flexible fiberglass blade and multiple sections were required to provide hinge-line flexibility. A hinge line near the low pressure side of the airfoil provides 60° of up flap and 10° of down flap capability for regulation and camber change. The flap system is more costly and offers no advantages over the baseline partial span control system.

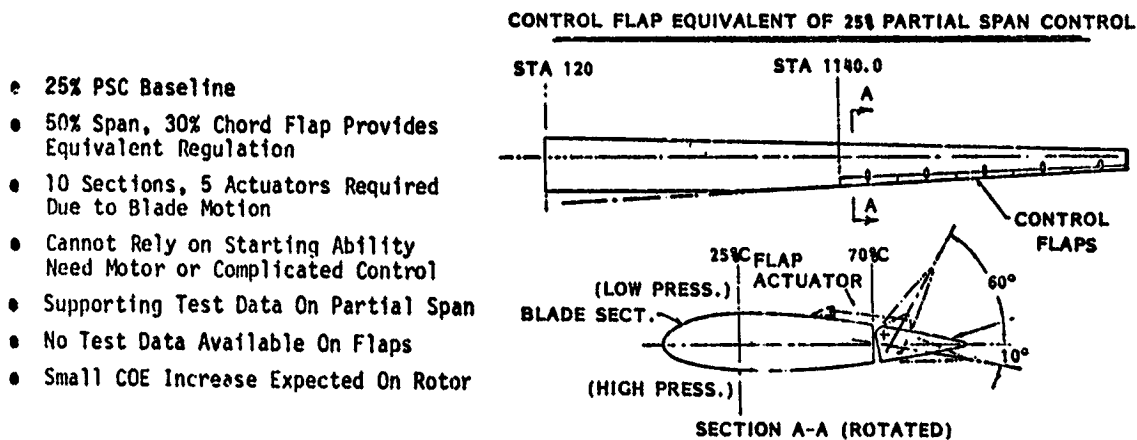


FIGURE 8. FLAP STUDY

### Multiple Speed

A comprehensive analysis of multi-speed operation was performed, utilizing the ratio between 2 speeds as the sizing study variable. An optimum shift point was determined by computation of output power at both speeds and shifting when the second speed provides higher power. An analysis with hourly data from Amarillo, Texas for 1978 and 1979 was also made.

Mechanical speed changing systems were examined with shift mechanisms that operated at no load while rotating (warm) and only when not rotating (cold). A reconnectable winding electrical system with warm shift for 2 speed operation, and a full variable speed electrical system were also examined.

Seasonal shifting (twice a year) was examined as an optional cold shift strategy, but energy capture was less than merely operating at a single speed because the torque limited system could not capture substantial high wind energy during the time it was in low speed.

The trade-off was made for three mechanical system operating modes and one electrical shifting mode. A constant torque for the drivetrain and a constant maximum rotor RPM were used.

The single speed system captures 95.5% of the energy that a system operating at maximum power coefficient from cut-in to rating would capture. This leaves only a 4.5% potential for improvement, and the warm shift systems obtain 3.1% of that 4.5% with all shift losses included.

A warm mechanical shift capability is better than cold shift; there is a small cost increase for the mechanism with a substantial increase in energy capture due to more rapid shift times. The electrical shift has more costly hardware than a mechanical shift and provides the same energy capture. Therefore, the lowest COE configuration is with a mechanical two-speed, warm shift.

### Nacelle Arrangement

A range of trade-offs were performed to determine the most cost effective method of supporting the rotor. Prior art, as used in the MOD-1 and MOD-2 WTG, employed a rotor support that was independent of the gearbox (stand-alone gearbox). This rotor support structure added size, weight and complexity to the nacelle. Several means of avoiding this were evaluated involving an upgrading of the gearbox input shaft and bearing and gearbox structure. The design that finally evolved incorporates a single rotor bearing in the gearbox structure, that transmits the rotor loads into the gearbox housing. The bedplate is designed to form a unified (but not integral) structure with the gearbox. The advantage of the rotor integrated gearbox design over the stand-alone gearbox can best be appreciated when one considers that the total nacelle weight of the MOD-1 WTG is 100 tons, while the total nacelle weight of the MOD-5A is 180 tons for over three times the power rating, and the nacelle dimensions are approximately equal.

### -sizing optimization

Many weight and cost estimating relationships (WCER's) were developed and verified during the course of Conceptual Design. These WCER's permit prediction of system cost and weight as a function of: rotor diameter, blade tip speed (determines main RPM), solidity (determines blade chord dimension and best efficiency vs. RPM), power density (determines power and torque ratings with diameter and tip speed), speed ratio (for two speed operation) and ground clearance.

Figure 9 illustrates the first tier of WCER and cost accumulation. The comment column summarizes what is included in each category and the percent contribution to cost of energy is indicated. At the second tier, the tower structure and the gearbox (part of the drivetrain) are the largest single COE contributors, at about 15% each.

A basic wind turbine, without installation, would be represented by categories 400 through 900, plus part of 1000 which equals about 65%. The other 35% represents installation and O&M related costs.

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1ST TIER CATEGORY	COMMENT	MODEL 204.2 \$/KWH
100 SITE	FOUNDATION AND GROUND EQUIPMENT	11.03
200 TRANSPORTATION	SHIPPING	3.07
300 ERECTION	INSTALLATION, INTEGRATION, CHECKOUT	6.36
400 ROTOR	BLADES, HUB, SHAFT, PSC SYSTEM	12.63
500 DRIVETRAIN	GEARBOX, SHAFTHING, GENERATOR	18.96
600 NACELLE	BEDPLATE, CONTROLS, HYDRAULICS, YAW	7.10
700 TOWER	TOWER, LIFT, CABLEING	14.99
800 REMOTE CONTROL	DISPATCHER INTERFACE	.07
900 SPARES	INITIAL SPARES AND SERVICES	.79
1000 SPECIAL	PROFIT, GROWTH, ASM/TEST	14.83
1100 LAND	SITE AND CLUSTER	.14
1200 CLUSTER	SUBSTATION, TRANSMISSION, ROADWAY	4.66
1300 OPERATION & MAINTENANCE	O/M LABOR, CONSUMABLES	6.44

FIGURE 9. WEIGHT AND COST ESTIMATING RELATIONSHIPS

### Optimization Procedure

Figure 10 depicts the procedure used to perform the system size optimization. For the set of variables noted above, aerodynamic performance is computed and used in conjunction with wind duration and system availability to determine the yearly energy capture. In parallel, costs (and weights) of the various system components and O&M are calculated to determine the annual cost and ultimately the COE. The computations are then repeated until an optimal set of variables is found. The entire procedure is embodied in the GE WINDOPT code, which in effect explores continuous parameter variations over input ranges of the sizing variables.

### Optimization Results

The present optimum MOD-5A system, Model 204.2, has a COE below 3 ¢/KWH (1980) as the result of Preliminary Design phase optimization. Figure 11 illustrates the cost and COE trends at Conceptual Design, where a minimum COE slightly above 3.3 ¢/KWH was predicted.

The minimum COE design is at 400 feet. The Statement of Work requirement of 3.75 ¢/KWH COE was met by MOD-5A WTG's with diameters from 325 feet to 450 feet.

The initial cost of the WTG increases dramatically with diameter. Higher cost is balanced by an even greater energy capture, resulting in a lower cost of energy for larger machines until above 400 feet, when capital cost tends to increase faster than energy capture, and cost of energy increases.

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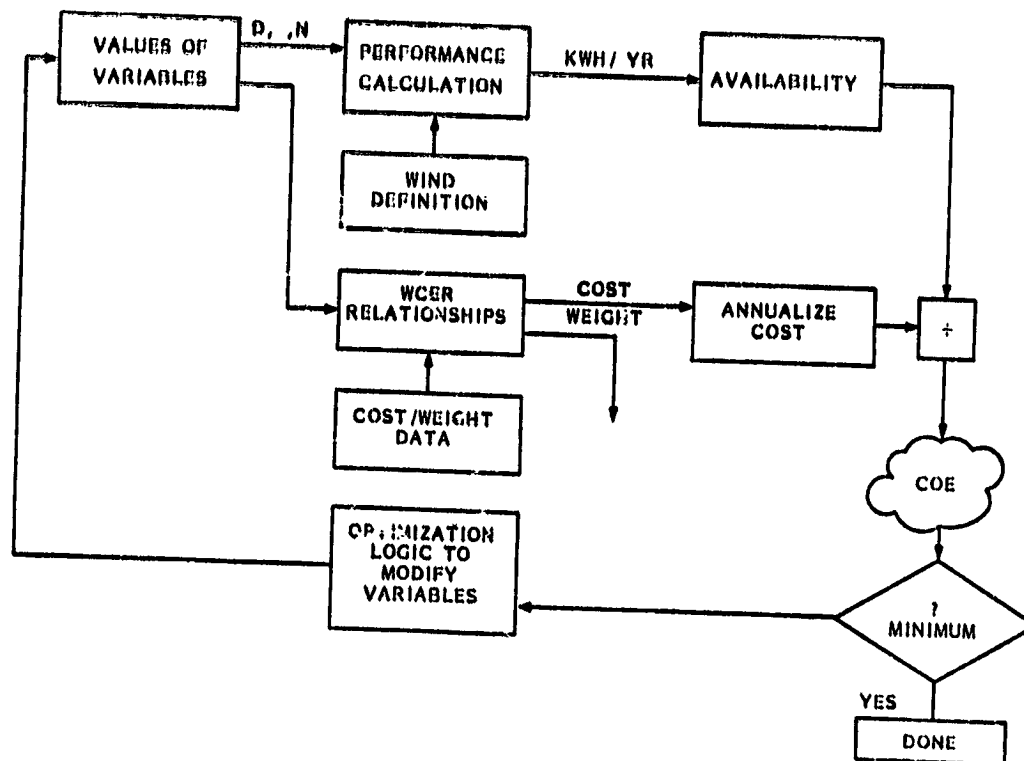


FIGURE 10. SIZING OPTIMIZATION FLOW

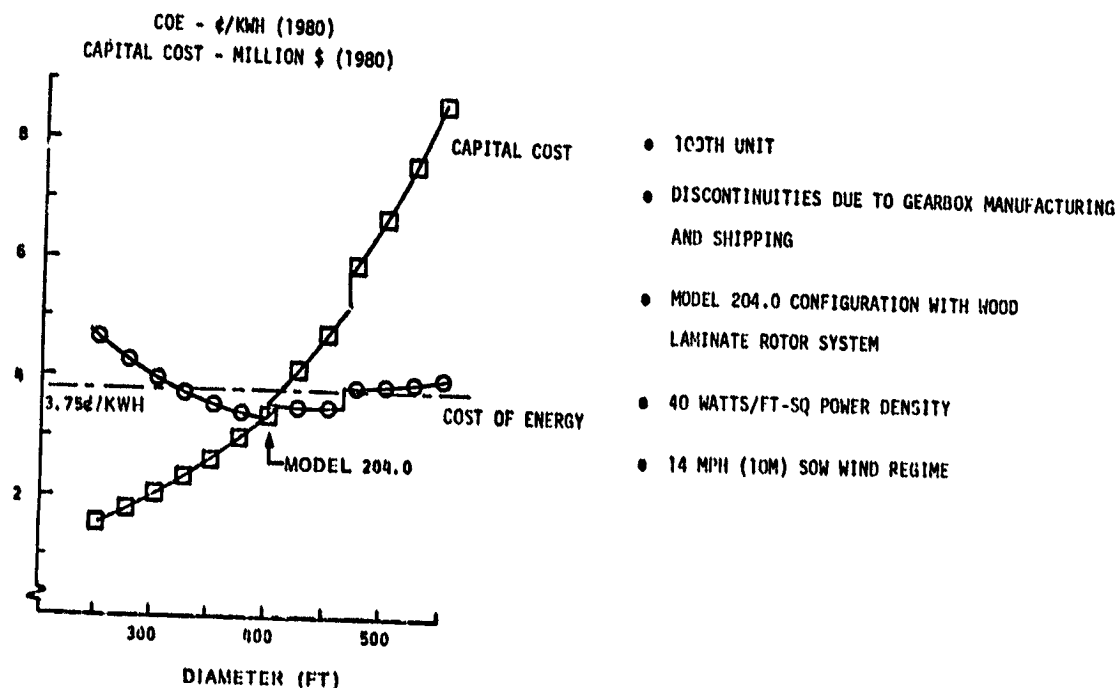


FIGURE 11. COE AND CAPITAL COST

Present Model 204.2 parameters are: Diameter 400 feet; Tip Speed 375 ft/sec. (17.9 RPM); Power Density 50 watts/ft-sq (6.2 MW); Ground Clearance 50 ft (250 ft. hub); Solidity 3.06%; Speed Ratio 1.35.

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Baseline System Definition

The MOD-5A Model 204.2 system features are defined in Figure 12.

<p><u>ROTOR</u></p> <ul style="list-style-type: none"> <li>• UPWIND</li> <li>• 375 FT/SEC TIP SPEED DESIGN</li> <li>• WOOD LAMINATE SPAN AND TIP</li> <li>• 64-6XX AIRFOIL, 3.06% SOLIDITY</li> <li>• 25% HYDRAULIC PARTIAL SPAN CONTROL</li> <li>• 13.25/17.9 (TWO-SPEED)</li> <li>• TEETERED 30 FT. STEEL HUB</li> <li>• 9° TILT <math>\pm 9^\circ</math> TEETER ALLOWANCE</li> <li>• HYDRAULIC POWER UNIT ON HUB</li> <li>• 277,800 LB ROTOR WEIGHT</li> </ul>	<p><u>DRIVETRAIN</u></p> <ul style="list-style-type: none"> <li>• ROTOR INTEGRATED HYBRID GEARBOX</li> <li>• 2.71 MILLION FOOT POUND TORQUE</li> <li>• FIRST STAGE PLANETARY, THEN SPLIT PARALLEL SHAFT ON END STAGE, THIRD STAGE AND SHIFTER</li> <li>• ROTATING SHIFT</li> <li>• STIFFNESS AND DAMPING CONTROL AT FIRST STAGE</li> <li>• TWO ROW ROLLER BEARING INTEGRATED INTO CASE FOR ROTOR AND GEAR SUPPORT</li> <li>• IN-LINE SLIP RING ACCESS</li> <li>• SHAFT DRIVE LUBE PUMP</li> <li>• HIGH SPEED SHAFT INCLUDES OVERLOAD RELEASE AND OVERRUNNING COUPLINGS</li> <li>• ROTOR LOCK AND PARKING BRAKE</li> <li>• 239,500 LB DRIVETRAIN WEIGHT</li> </ul>	<p><u>NACELLE</u></p> <ul style="list-style-type: none"> <li>• BEDPLATE WITH WIRING, PLUMBING, RUNS UNDER FLOORING</li> <li>• YAW HYDRAULICS SYSTEM</li> <li>• GEARBOX AND BEARING LUBRICATING SYSTEM</li> <li>• CONTROL ELECTRONICS</li> <li>• PUSH-PULL YAW DRIVE</li> <li>• YAW BEARING ASSEMBLY ATTACHED TO TOP TOWER SECTION</li> <li>• YAW SLIP RING</li> <li>• 116,956 LB WEIGHT</li> </ul>
<p><u>ELECTRICAL</u></p> <ul style="list-style-type: none"> <li>• 6200 KVA OIL-FILLED TRANSFORMER</li> <li>• WALK-IN AISLE SWITCHGEAR AND CONTROL ENCLOSURE</li> <li>• 69 KV NOMINAL INTERFACE VOLTAGE</li> <li>• RADIAL FEEDER-TYPE CLUSTER ARRANGEMENT</li> <li>• 6.2 MW SYNCHRONOUS GENERATOR</li> </ul>	<p><u>TOWER</u></p> <ul style="list-style-type: none"> <li>• 14.5 FT CYLINDRICAL STEEL</li> <li>• 250 FT TG HUB</li> <li>• TAPERED BELL SECTION FOR TUNING</li> <li>• INTERNAL LIFT</li> <li>• 490,000 LB WEIGHT</li> </ul>	<p><u>FOUNDATION</u></p> <ul style="list-style-type: none"> <li>• SPREAD FOOTING, REINFORCED CONCRETE</li> </ul>
<p><u>MAINTENANCE</u></p> <ul style="list-style-type: none"> <li>• PERMANENT CLUSTER CREW</li> <li>• SPARES BUDGET</li> </ul>		

FIGURE 12. MODEL 204.2 DEFINITION

A spread footing tower foundation with triple reinforcing and embedded anchor studs is utilized for most soil densities. The soil flexibility is included in the tower frequency analysis. Rock or very soft soils would require a departure from the basic general purpose foundation after soil analysis.

Electrical protection and interface equipment is located away from the tower base to provide maintenance vehicle access. Factory wiring is provided for the walk-in control enclosure. A window is provided for operator observation of the rotor during manual operations.

The baseline cluster is rated at 150 MW with 25 MOD-5A units. A multiple grid tie is provided with 69 KW cluster distribution. Each WTG has a step-up transformer that limits short circuit duty on the site contactor as well as providing a voltage match. A central spares store and a permanent 4 man cluster maintenance crew are utilized to minimize maintenance costs.



## SUB-SYSTEM DESCRIPTIONS

### Rotor Blade

The selection of the MOD-5A rotor blade configuration and material was based on the results of an extremely comprehensive system/subsystem trade study. This study defined the 100th unit costs of the three blade materials and explored diameters ranging from 150 to 500 feet.

Initial parametric cost and weight variations were determined for the three materials and iterated based on system performance evaluation. First results indicated that wood laminate had lower cost and weight than fiberglass, with steel a poor third. However, the wood laminate blade required a thicker section due to its relatively lower strength. This thicker blade, when configured as a 230XX airfoil, provided less energy capture than the thinner fiberglass airfoils. An alternate high performance thicker airfoil series 64XXX, which can be readily fabricated in wood laminate but not in fiberglass or steel, allows the thicker wood laminate blade to have performance similar to the thinner 230XX fiberglass blade, and swung the decision to wood laminate.

The blade is constructed of 0.10 inch thick rotary cut douglas fir laminate, which is epoxy bonded at room temperature, using vacuum bags, to form the major load carrying forward portion of the blade. The trailing edge portion of the blade is constructed of plywood faces with a paper honeycomb core sandwiched between them. The upper and lower surfaces are laminated in female molds which assure excellent contour control, and then bonded together, including the shear web, to complete a section assembly. The outer surfaces of the blade are covered with epoxy and fiberglass cloth as part of the molding operation. The blade construction is similar to that successfully used on MOD-0A and hence presents a minimal development risk consistent with the MOD-5A program philosophy. See Figure 13.

### Partial Span Control Mechanism

A description of this mechanism is shown on this simplified conceptual drawing (Figure 14). The steel weldments, shown enclosing the spindle shaft, include airfoil shaped skins, longitudinal spars and stiffener ribs at both ends. Not shown is a "thrust tube" which surrounds the inboard end of the spindle shaft between the two bearings. This tube provides the interface with the bearings, and reacts the radial forces into the rib at the inboard bearing location. The tube carries the centrifugal force of the tip from this bearing outboard to the rib at the radial bearing, where it is bolted in and distributes this force into the box structure formed by the two spars and skins immediately surrounding the shaft. The tube, shaft, and bearings form a separate assembly.

Loads from the outboard tip portion of the PSC subassembly are introduced into the shaft by a bolted connection at the outer rib and a bushing joint at the inner rib. The spar arrangement is the same in both sections. The actuator is mounted at the midpoint of the body

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to minimize the bending moments on the cylinder created by the inertial forces of the actuator under the normal centrifugal acceleration of approximately 20 g's.

Since the drag force provided by one fully feathered tip is sufficient to stop the rotor, dual redundancy has been provided in the hydraulics to ensure that a least one tip will be feathered reliably for a safe shutdown in case of a failure.

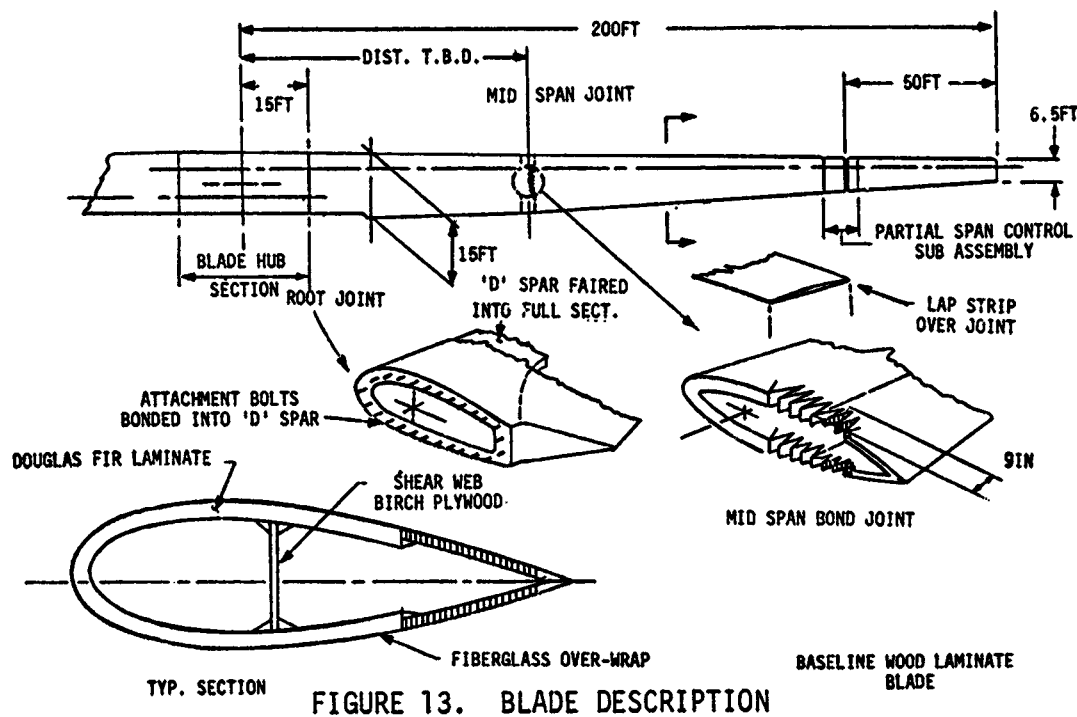


FIGURE 13. BLADE DESCRIPTION

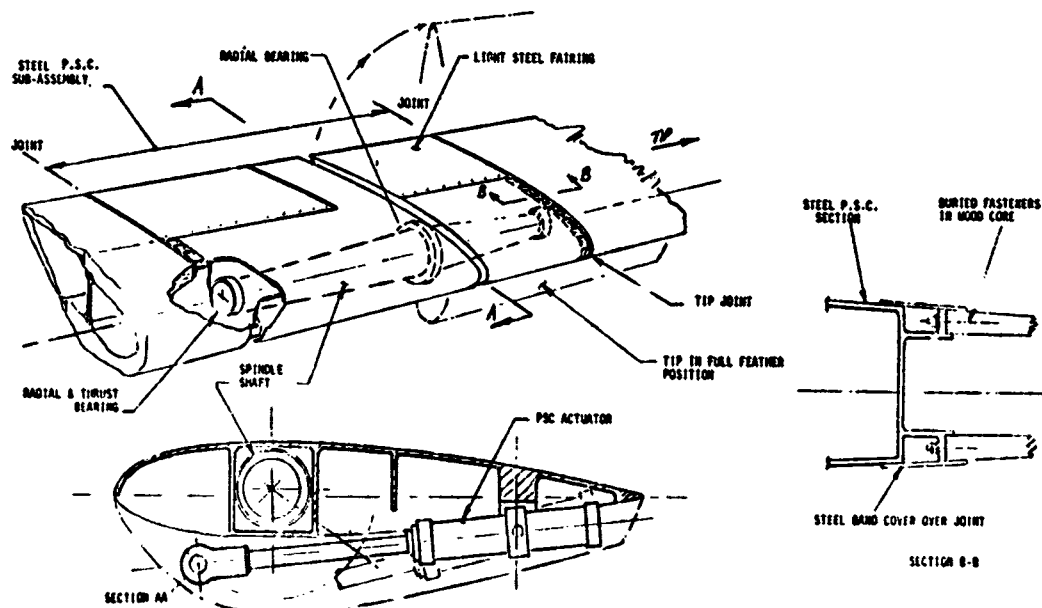


FIGURE 14. PARTIAL SPAN CONTROL MECHANISM

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### Nacelle Assembly

Wind energy, captured by the rotor at relatively low specific power density over the large area swept by the blades, is "concentrated" by the gearbox and generator located in the nacelle. The large diameter blades result in a massive structure that must be supported safely under all environmental conditions and wind speeds. The nacelle and gearbox provide the means of transmitting the static and dynamic loads safely from the rotor into the tower and hence, into the ground.

It was always known that weight in the nacelle meant a cost penalty. Accordingly, an intense effort was made to reduce as much structure in the nacelle as possible consistent with performance requirements. This led to the selected rotor support method whereby the rotor bearing is integrated into the first stage of the gearbox, assuring a compact gearbox, bedplate and nacelle. The concept is shown in Figure 15.

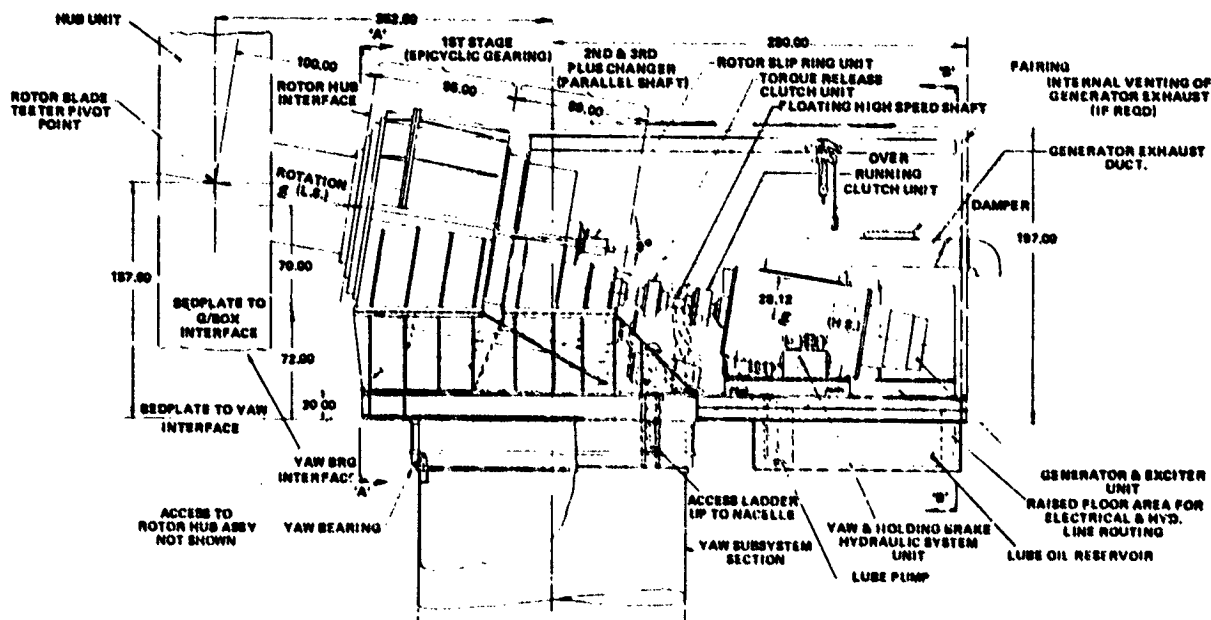


FIGURE 15. NACELLE CROSS SECTION

The gearbox and bedplate were designed as a unified load carrying structure between rotor and tower. A cantilevered section of bedplate supports the generator and power accessory equipment. A fairing assures a secure and weather-protected work environment during routine maintenance. The function and cost effectiveness of each element was carefully thought out to assure a low COE and maintainability. This is reflected in the compact gearbox and bedplate and an adequate work space. Access to all critical elements is provided by means of roof hatches, removable floor gratings, and ladders.

### Rotor Integrated Hybrid Gearbox

The MOD-5A gearbox is advanced gearbox technology applied to wind turbine generators. It incorporates technological innovations in the epicyclic first stage and features borrowed from other applications,

such as the torsion bar ring gear suspension used primarily in Basic Oxygen Furnace (BOF) drives, to provide drivetrain compliance. The most rewarding design feature is the integration of the rotor support bearing into the gearbox structure. This alone resulted in a significant savings in size, weight and cost of the overall nacelle by eliminating a separate shaft, and the attendant radial and thrust bearings, gear couplings and bearing pedestals associated with a conventional rotor support, not to mention the extra length of bedplate necessary to accommodate the rotor support assembly. Although the epicyclic implementation of the first stage was found to be most cost effective, succeeding stages were evaluated individually. Accordingly, parallel shaft gearing in the second and third stages was found to offer a significant cost advantage at a small weight penalty. Parallel shaft gearing in the third stage also made it feasible to incorporate a speed changer without increasing the gearbox envelope. See Figure 16. To provide load alleviation and minimize power swings, compliance and damping are required. The drivetrain provides this by hydraulically damping the torsion bar suspension of the epicyclic first stage. The speed changer permits extending energy capture into the lower wind regimes to enhance the COE.

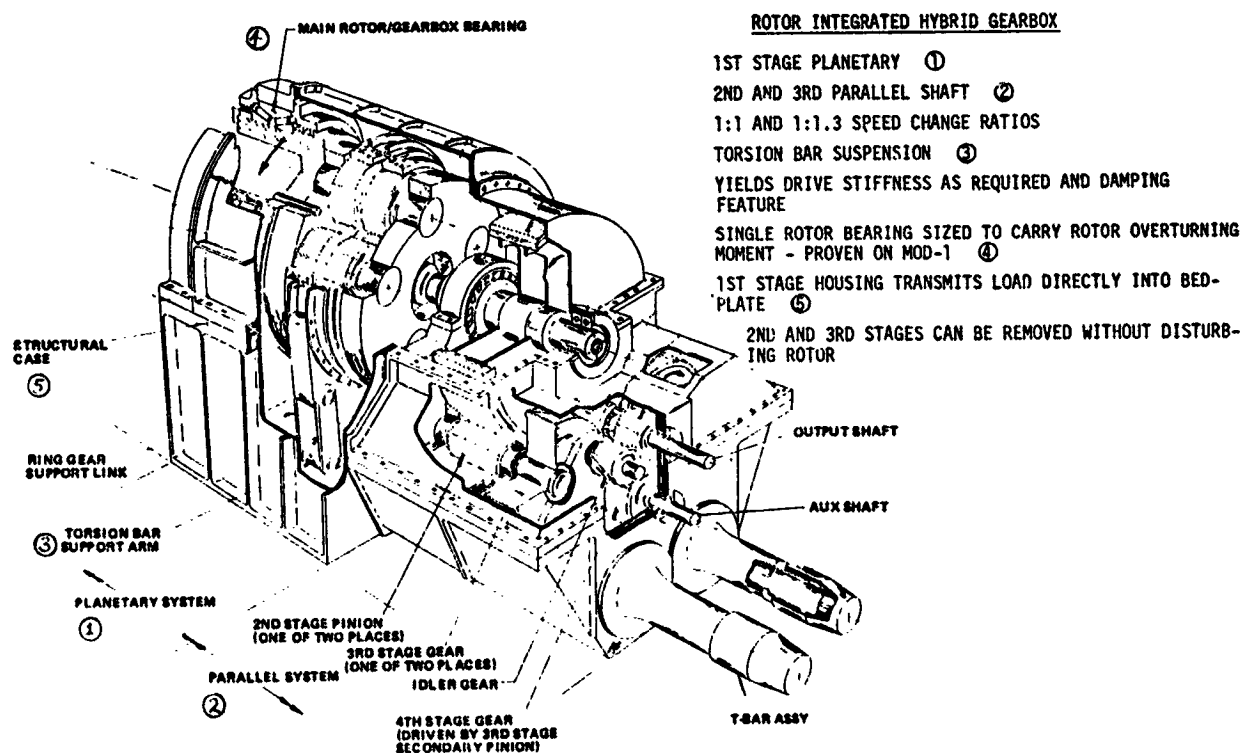


FIGURE 16. ROTOR INTEGRATED HYBRID GEARBOX

### High Speed Drivetrain

The high speed drivetrain connects the gearbox output shaft to the generator input shaft. It contains a flexible coupling feature to provide for axial and angular misalignment. Two additional functions are

incorporated for operational reasons. One is the torque overload release clutch, which will protect the drivetrain from damage due to excess torque levels (clutch disconnects when the torque level exceeds  $1.75 \times$  nominal). The other is an overrunning clutch which will allow the generator to motor when the input speed falls below synchronous speed. The overrunning clutch also assists in providing a smooth transition during speed changing sequence.

### Tower and Foundation

The thin tube concept as the basic tower structure has many advantages. It is very efficient in carrying the blade and nacelle bending and torsional loads imposed under normal and abnormal conditions. It provides an all-weather access to the nacelle. But of most importance, it costs less than a comparable truss structure. The tube is not as stiff as a truss structure, but if the system natural frequencies are carefully selected, this can be an advantage also. By placing the first bending frequency between 1P (one per rev. of the blade) and 2P, system dynamic load trade studies have shown rotor, nacelle, and tower loads to be reduced over those of a stiffer truss tower.

The importance of an optimum tower and foundation design is seen from its contribution to the COE figure. The sum is the largest contribution, and the tower design affects foundation costs. During the trade studies conducted by Chicago Bridge and Iron (CBI), several cases were found where the least expensive tower design did not yield the lowest overall cost.

### Yaw Drive System

A conceptual layout of the yaw system is shown in Figure 17 along with the main features. The lift terminates at the upper platform. Access to the nacelle is by ladder up through the nacelle floor providing all-weather access. The yaw drive and slip ring assemblies are also easily accessible from inside the tower, as well as the bearing bolts.

To fulfill its design requirements, the yaw drive has to be neither fast acting nor highly precise because of the nature of the wind. The rotation of the nacelle is similar in function to the azimuth drives of cranes, power shovels, rotary derrick, etc. The conventional design uses a single large slewing type bearing with gear teeth integrally cut into either the inner or outer race. A hydraulic motor then drives it with a pinion gear. During conceptual design, methods to reduce the cost centered on elimination of the gearing cost.

The selected concept uses the brake disc (fixed to the tower) which is required in any design, and brakes called grippers mounted on the end of a hydraulic cylinder to push or pull the nacelle around. A similar yaw drive concept is used on the Hawaiian MOD-OA design. Without the gearing there are no backlash problems or precise gear mounting requirements. The stiffness of the yaw drive is dictated essentially by the drive hydraulic cylinders and is only a matter of concern when rotating the nacelle.

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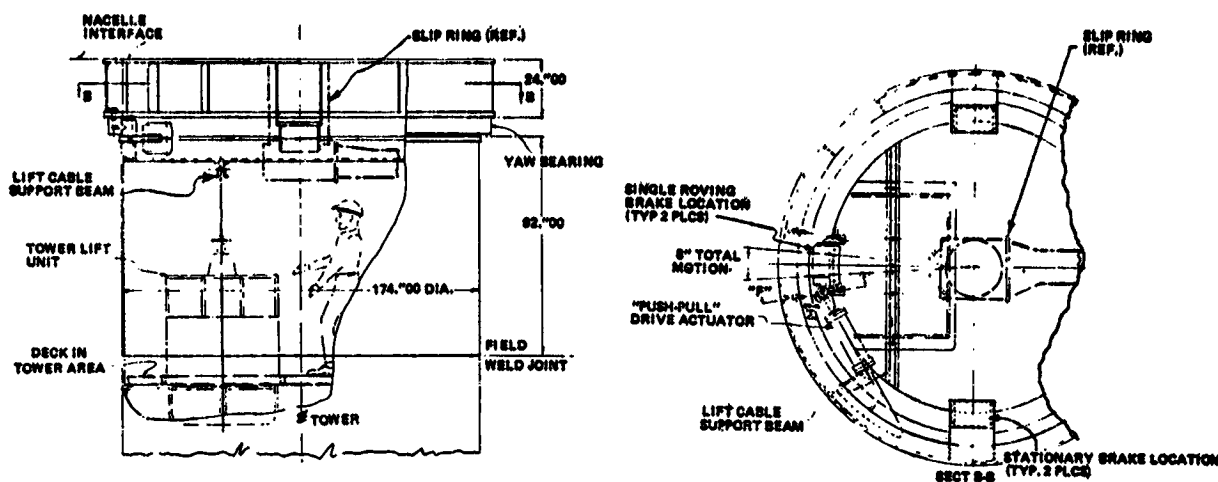


FIGURE 17. YAW DRIVE SYSTEM

### Controls Equipment

Several trade-offs made include the type of control, type of processing, location of the central electronics, and the criteria for hardware implementation. The selected design will minimize development by maximum use of proven technology. The conceptual design uses multi-loop control and digital processing, with the control electronics located in the nacelle. The hardware implementation will use proven modular electronics with a minimum of special design and development of the interface circuitry. An operator on site or at a remote location can obtain data and supervise automatic system operation.

### Power Generation Equipment

Power generation equipment, with the exception of the yaw slip ring assembly, is standard with optional features. This "off the shelf" approach provides for lower cost and more realistic delivery times. When considering synchronous generators above a rated output of 4000 KVA, 1800 RPM is no longer cost effective; therefore, 1200 RPM was chosen for the baseline 6400 KVA design. By choosing the operating voltage at 5500 instead of the more common 4160 volts, the additional cost for the generator is more than offset by enabling the use of a synchronous motor starter instead of a more costly high current switchgear assembly. Step-up at each wind turbine is provided to minimize interconnection losses.

### CONCLUSION

The MOD-5A design concept is an innovative next generation machine, which meets its COE requirement with minimum technical risk.

CONCEPTUAL DESIGN OF THE 7  
MEGAWATT MOD-5B WIND TURBINE GENERATOR

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**ABSTRACT**

Similar to MOD-2, the MOD-5B wind turbine generator system is designed for the sole purpose of providing electrical power for distribution by a major utility network. The objectives of the MOD-2 and MOD-5B programs are essentially identical with one important exception; the cost-of-electricity (COE) target is reduced from 4¢/Kwhr on MOD-2 to 3¢/Kwhr on MOD-5B, based on mid 1977 dollars and large quantity production.

The MOD-5B concept studies and eventual concept selection confirmed that the program COE targets could not only be achieved but substantially bettered. Starting from the established MOD-2 technology as a base, this achievement resulted from a combination of concept changes, size changes, and design refinements. The result of this effort is a wind turbine system that can compete with conventional power generation over significant geographical areas, increasing commercial market potential by an order of magnitude.

**INTRODUCTION**

MOD-5B is under the overall management of the U. S. Department of Energy, with direct management assigned to NASA-Lewis Research Center. Like MOD-2, it is being developed for the sole purpose of generating electricity that can be economically fed into a utility grid. While it is generally considered a third generation large horizontal axis wind turbine, it is more realistically a second generation (to MOD-2) machine with respect to turbines that have been optimized for commercial power production.

A little over two years ago a similar paper [1] was presented by the author at the April 24-26, 1979, workshop in Cleveland describing status of the MOD-2 wind turbine system development. At that time, the major message was that MOD-2 incorporated most of the concepts that showed promise for major reduction in the cost-of-electricity (COE) but that significant gains in the future were still achievable by additional concept changes coupled with component-by-component improvement, using experience from MOD-2 fabrication, test, and operation. Nothing that has occurred since that time has changed this premise. We have been very pleased with the concepts selected for MOD-2. Even so, MOD-5B does show a substantial gain in operating economics with respect to MOD-2. It is the intent of this paper to explain how and where these gains occurred. Frequent comparisons will be made to MOD-2, which represents the technical base from which MOD-5B evolved.

## PRIMARY SPECIFICATIONS AND REQUIREMENTS

The major MOD-5 requirements imposed on the contractors are as follows:

- o Shall be designed for electrical utility use.
- o Shall generate no less than 1 megawatt of three phase, 60Hz, power into the grid.
- o Shall achieve a COE of 3¢/Kwhr or less in mid 1977 dollars. (This compares to a 4¢/Kwhr requirement on MOD-2.)
- o Shall attain a 30 year life.
- o Shall operate at unattended remote sites.
- o Shall be a horizontal axis propellor type configuration.
- o Shall be designed for 6.3 m/s (14 mph) yearly mean wind speed and a maximum wind velocity of 53.6 m/s (120 mph), both at 10 m (30') above grade.

Numerous other requirements were imposed with respect to safety, network protection, gusts, lightning strike, seismic disturbance, availability, controllability, instrumentation, analytical methods, environmental conditions, etc. For the complete requirements and specifications, refer to the MOD-5B Statement of Work [2].

## CONCEPTUAL DESIGN DEVELOPMENT

The MOD-5B concept development effort was conducted over an approximate seven month period. During this phase, twenty two major trade studies (see Table I) were conducted and reported on in significant detail. In the interest of brevity, only those studies that most impacted the selected configuration or went beyond the scope of the MOD-2 studies will be reported in detail.

### Rotor

One concept that has always appeared attractive is the fixed pitch rotor system. Though seemingly simple, in large machine sizes it is a more technically challenging and risky concept than the apparently more complex variable pitch systems. This results from the need to safely stop the machine in an emergency and the necessity of developing a rotor that is efficient, stalls gently, is economical to build, and limits both dynamic and static loads. The loads problem is, in the final analysis, the decisive factor. Figure 1 illustrates that the peak power of the fixed pitch rotor system is over 50% greater than that of the variable pitch system, resulting in comparable rotor and drive train load increases. These loads are further amplified by the inability to attenuate dynamic torque overshoots to the degree



possible with a variable pitch system. The result is a very substantial increase in rotor, drive train, and generator weights and costs, offset by an increase of 5% in annual energy produced as illustrated in Figure 2. During the concept studies a competitive fixed pitch rotor system was developed, including wind tunnel testing to assure satisfactory stall characteristics. Despite giving the system every benefit of the doubt, the fixed pitch system could not be shown quite as cost effective as variable pitch, even though it could meet the MOD-5 COE target. Therefore, a partial span variable pitch system was selected. It is probable that a fixed pitch system would prove cost effective on smaller machines where the costs involved in variable pitch control are relatively large.

Another interesting concept that could very well prove cost effective on smaller machines is a rotor center disk to accelerate the velocity of the wind outboard of the disk. This concept (see Figure 3) was evaluated, including wind tunnel testing that showed annual energy production was increased by about 5%, normally a gain that would appear extremely attractive. Unfortunately, the cost of the disk itself, combined with the increased tower and foundation costs resulting from high wind loads, showed the concept to be non cost effective for the MOD-5B.

Numerous minor geometry changes from the MOD-2 developed shapes were incorporated into the MOD-5B rotor, with the biggest gain from solidity ratio, taper ratio, and t/c changes that resulted in a relatively lightweight and efficient rotor. Although, wood and fiberglass were evaluated in detail, steel construction was again found superior in overall cost effectiveness except for the tip, where wood's smoothness and ability to be fabricated to complex shapes offset the performance losses resulting from the additional deflection.

#### Generator System

The study to select the optimum generator system for MOD-5B was perhaps the most comprehensive of the concept phase studies. Conducted with the assistance of the Westinghouse Corporation, the matrix of potential generator systems illustrated in Figure 4 was first reduced to three; the best single speed system, the best multi-speed system, and the best variable speed system. These three systems were evaluated in detail, including the cost and performance impact of not only the generator system itself but of all other wind turbine system components. Probably the most decisive factor in making the final selection was the dynamic simulation of the competitive systems as illustrated in Figure 5. Even without the quill shaft, the means used to attenuate the large "two per revolution" torque oscillations in the single and two speed systems, the variable speed generator reduced the torque overshoots from approximately 20% to 2%. This permitted not only deletion of the quill shaft but also a reduction in size of all drive train components. These savings, coupled with an increase in annual energy production as illustrated in Figure 6, more than compensate for the very sizeable additional cost of the variable speed system.

An interesting example of the operational flexibility of this system is shown in Table 2, indicating that useful power can be produced a much larger percent of the time during periods of relatively low winds. The impact of this additional operating time on the ability of wind systems to be given "capacity credit" by the utilities may prove to be one of the most valuable, though intangible at this time, system advantages.

#### Miscellaneous Component Refinement

During the final design, fabrication, test, and operational phases of the MOD-2 program, a number of areas were recognized where additional refinement could reduce component cost or improve performance. These potential improvements fall in three general classifications, all of which were incorporated into the MOD-5B design.

The first classification results from operational data that indicates growth is available because overstrength or oversizing was introduced into some components as a result of conservative loads and analysis. The drive train, particularly the gearbox, is the outstanding example. The active pitch control system, coupled with the quill shaft, attenuated torque oscillations in the drive train far more than predicted. As a result, the gearbox was substantially oversized on MOD-2. The reduced sizing on MOD-5B accounts for a very substantial system saving.

The second classification of component improvements results from recognition during MOD-2 fabrication and assembly that specific hardware component designs, though functionally adequate, could benefit from producibility improvements to reduce production costs. Examples applied to MOD-5B include an all new plate girder type nacelle structure, new rotor tip spindle designs, revised rotor teeter bearing geometry, and revised foundation geometry.

The third classification of component improvement results from recognition that more refined analytical techniques could decrease costs or increase performance. Examples applied to MOD-5B include a sophisticated rotor parameter analysis program that permitted evaluation of literally thousands of variations, resulting in both increased performance and reduced weight and a tower optimization program that solves for the lightest weight tower that precisely satisfies the strength, stiffness, and fatigue requirements.

#### Machine Size Optimization

The development of weight and cost trend data for use in the machine size optimization studies was in itself a major project. The MOD-5B wind turbine system was broken down into over fifty separate packages for which parametric cost estimating relationships were established, using experience from MOD-2, supplier data, and Boeing estimating techniques applicable to quantity production of large complex systems.

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The resulting sizing programs were checked by designing four point design systems; 101.9 m (228'), 135.9 m (304'), 169.9 m (380'), and 187.7 m (420') diameter. The confirmed trending curve is shown in Figure 7, indicating that lowest cost-of-electricity occurs at approximately a 187.7 m (420') rotor and 7200 KW power rating.

The rather obvious question arises as to why the MOD-2 optimized at 134.1 m (300') and the MOD-5B at 187.7 m (420'). Although the cumulative effect of many small changes in the cost estimating relationships played a part, three major changes were primarily responsible:

- o Smaller gearbox sizing as a result of reduced torque overshoots found possible with the MOD-2 type active control system and with the use of the variable speed generator.
- o On MOD-2, supplier inputs indicated that gearbox costs increased as a function of low speed torque to an exponent of 1. Using experience from the gearbox that was actually developed for MOD-2, it was found this growth exponent could be substantially reduced.
- o New crane designs that have been recently developed substantially reduce the erection cost increase with size that prevailed at the time of the MOD-2 studies. The dedication of these cranes to both original erection and subsequent maintenance of large wind farms further reduces both erection and maintenance cost increase with size.

Cost of Electricity (COE)

Although the predicted COE at the start of the MOD-5B concept phase was slightly under the program target (3¢/Kwhr in 1977 \$), it was generally anticipated that achievement of that goal during the hardware definition program phases would prove a formidable task. Surprisingly enough, as a result of the concept studies discussed above, the COE actually trended downward as the program progressed. At this point in the program (early in the Preliminary Design Phase) it would take a tremendous and unexpected technical setback if the COE target were not achieved. This is true in spite of the fact that the MOD-5 formula for computing COE is considerably more stringent than on the MOD-2 program, as follows:

COE (cents/kwh) =

$$\frac{(\text{Installed equipment costs, \$}) (18)}{\text{Annual kwh}}$$

$$+ \frac{(\text{Intra cluster costs, \$}) (18)}{\text{Annual kwh}}$$

$$+ \frac{(\text{Land costs, \$}) (15)}{\text{Annual kwh}}$$

$$+ \frac{(\text{Periodic replacement costs, \$}) (\text{Periodic levelizing factor}) (100)}{\text{Annual kwh}}$$

$$+ \frac{(\text{Annual O\&M costs, \$}) (200)}{\text{Annual kwh}}$$

The scenario used on the MOD-5B program for determining COE is based on the following:

- o Cost of 100th unit of a 1000 unit production run.
- o A dedicated manufacturing facility designed and tooled to accommodate production of approximately 20 units per month.
- o Installation in wind farms of at least 25 units. (Preferably as many as 60 units.)

### SELECTED CONCEPT DESIGN

The essential elements and features of the MOD-5B wind turbine system that evolved from the concept phase studies are illustrated in Figures 8 through 11. While there is an almost daily change in detail costs and weights, no major size or concept changes are anticipated during the preliminary and final design phases of the program.

### CONCLUSIONS AND PROBLEMS

If produced under the program scenario of large quantity production in an optimum facility, MOD-5B can compete with conventional power generation over much larger geographical areas than was possible with previous systems. However, large scale commercialization of large wind turbines suffers from the chicken and egg syndrome. That is, costs of units are so high when produced one or two at a time on prototype tooling that the utilities can scarcely afford to buy them. On the other hand, industry cannot possibly afford to invest the huge capital required for an automated high rate production capability without an established order base. To break this log jam will require a great deal of cooperation between government, industry, and the utilities. We intend to do our part to achieve this end.

### REFERENCES

1. Douglas, R. R., "The Boeing MOD-2 Wind Turbine System Rated at 2.5 MW", presented at the Large Wind Turbine Design Characteristics and R&D Requirements workshop, Cleveland, Ohio, April 24-26, 1979, NASA Conference Publication 2106.
2. NASA Contract DEN3-200 Statement of Work - Exhibit B - Requirements and Specifications, Aug. 1, 1980.

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**TABLE 1. CONCEPT TRADE STUDIES.**

**System Configuration Studies**

- SC-1 MOD-5B baseline compared to modified MOD-2
- SC-2 Free yaw
- SC-3 Variable pitch versus fixed pitch
- SC-4 Optimum machine size

**Rotor Studies**

- R-1 Blade aerodynamics
- R-2 Material selection
- R-3 Center disk
- R-4 Rotor control (braking, etc.)

**Drive Train Studies**

- DT-1 Soft drive configuration
- DT-2 Gearbox configuration
- DT-3 Gearbox mounted rotor
- DT-4 Generation variations

**Nacelle Studies**

- N-1 Unitized steel shell versus truss
- N-2 Configuration optimization

**Tower Studies**

- T-1 Tower frequency and diameter
- T-2 Tower height

**Miscellaneous Studies**

- M-1 Erection method
- M-2 Cluster optimization
- M-3 Production optimization
- M-4 Component producibility
- M-5 Foundation

**TABLE 2. EXAMPLE OF LOW WIND ENERGY CAPTURE, SINGLE SPEED  
VERSUS VARIABLE SPEED GENERATORS.**

**Ground rules**

- Data based on Goldendale MOD-2 site winds 12/8/80 thru 2/8/81 (Hourly averages of continuous strip-chart data).
- Assumes a MOD-5B type variable speed generator installed on MOD-2 with 2,500 kW peak power.

**Total winds 12/8/80 thru 2/8/81**

- |                            |   |  |
|----------------------------|---|--|
| • Single speed generator   | { | Energy generation potential = 469 MWH<br>Hours operation = 352 hours               |
| • Variable speed generator | { | Energy generation potential = 536 MWH (+14%)<br>Hours operation = 642 hours (+82%) |

**Low winds [below 8.9m/s (20mph)] 12/8/80 thru 2/8/81**

- |                            |   |   |
|----------------------------|---|---|
| • Single speed generator   | { | Energy generation potential = 102 MWH<br>Hours operation = 143 hours                |
| • Variable speed generator | { | Energy generation potential = 150 MWH (+47%)<br>Hours operation = 433 hours (+203%) |

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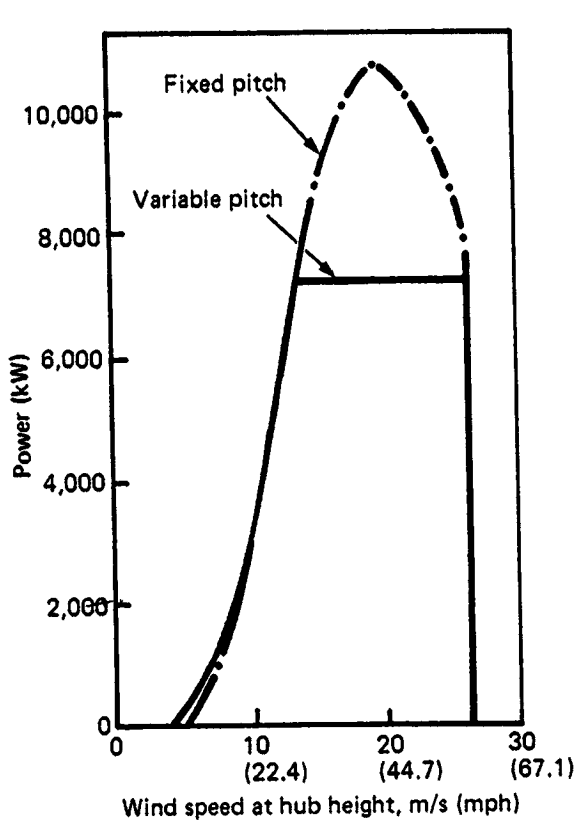


FIGURE 1. VARIABLE PITCH VERSUS  
FIXED PITCH POWER  
COMPARISON

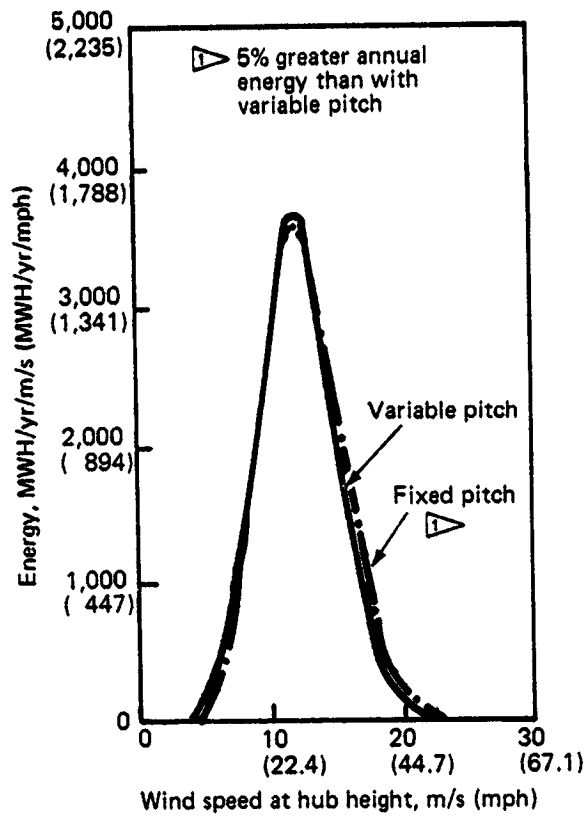


FIGURE 2. VARIABLE PITCH VERSUS  
FIXED PITCH ENERGY  
COMPARISON

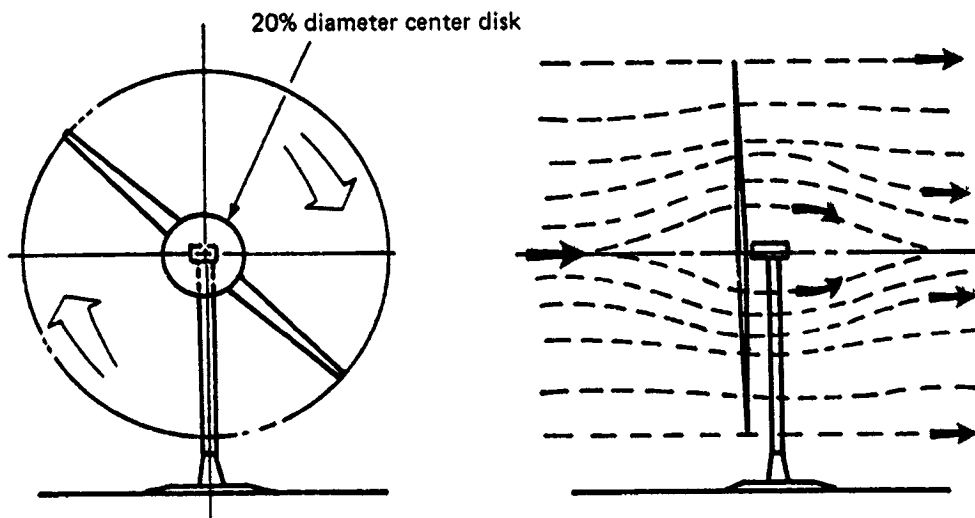


FIGURE 3. CENTER DISK TEST CONFIGURATION

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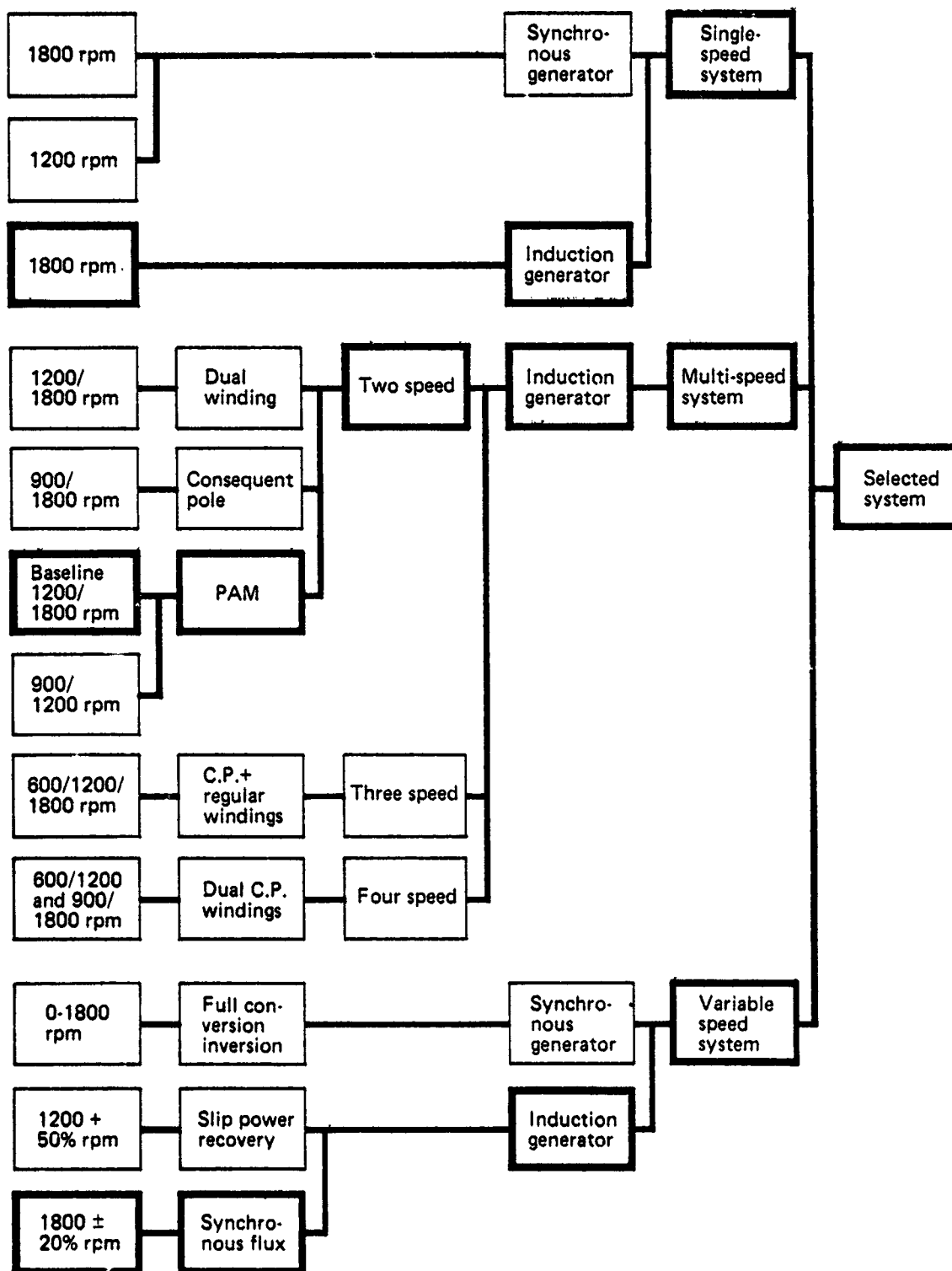


FIGURE 4. GENERATOR SYSTEM STUDY MATRIX

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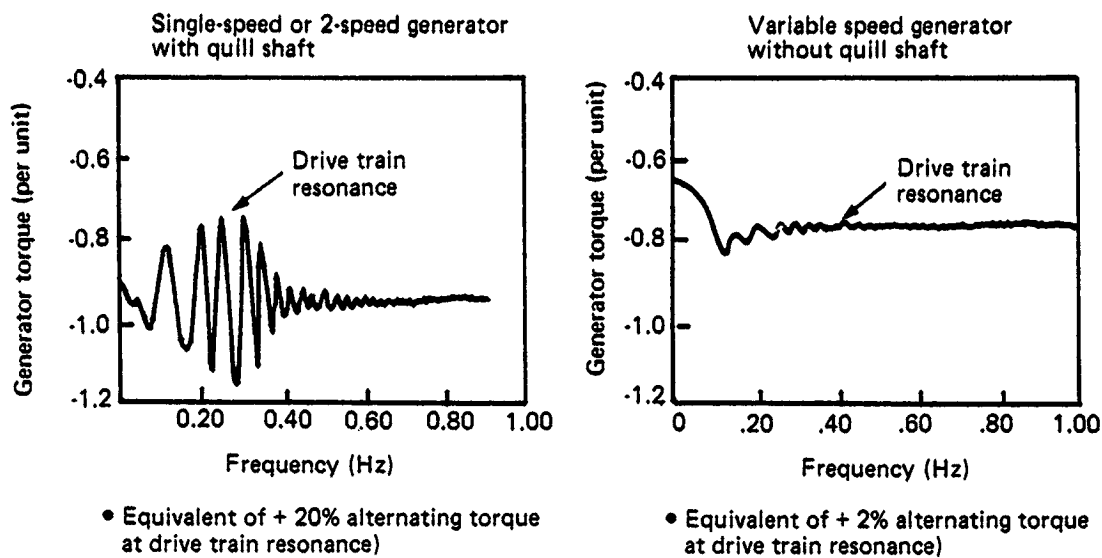


FIGURE 5. ALTERNATING TORQUES AT DRIVE TRAIN  
NATURAL FREQUENCY – DYNAMIC SIMULATION

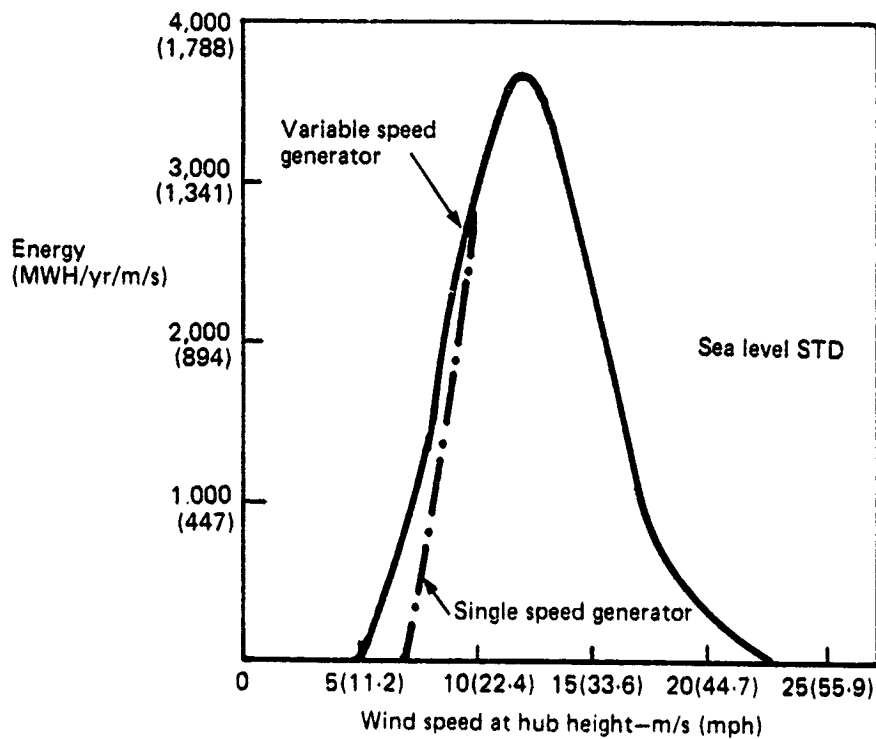


FIGURE 6. VARIABLE VERSUS SINGLE SPEED GENERATOR  
ENERGY CAPTURE



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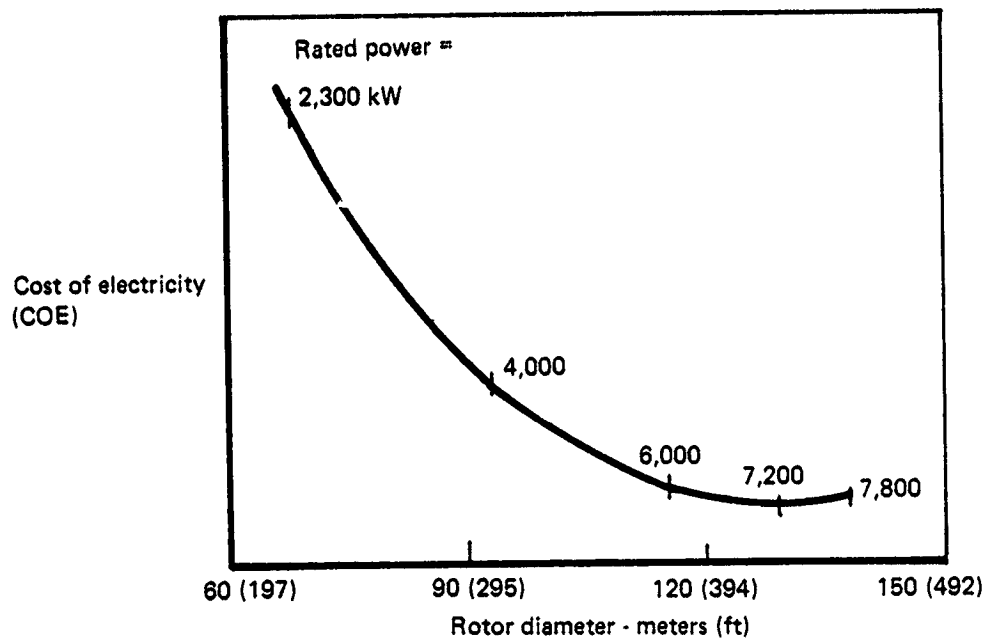


FIGURE 7. COE VERSUS MACHINE SIZE TRENDS

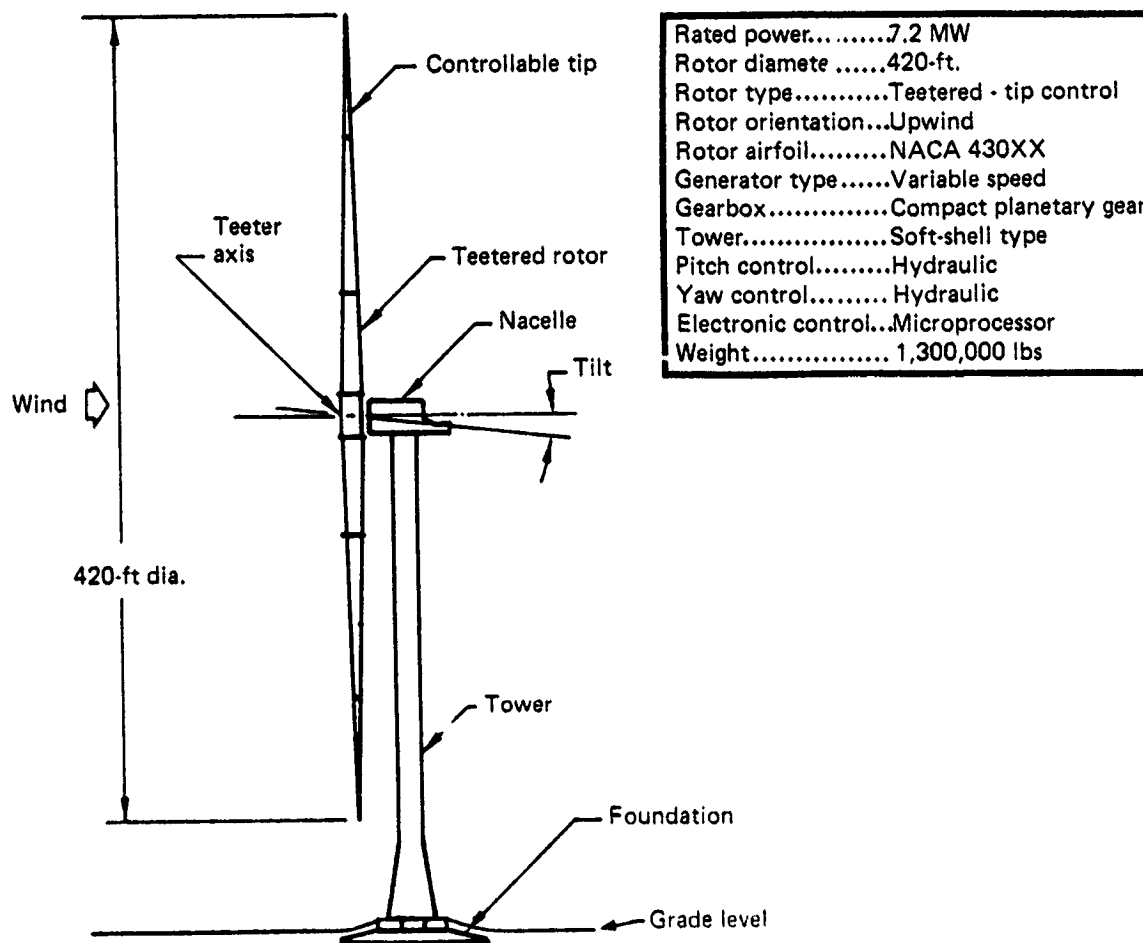


FIGURE 8. MOD-5B GENERAL ARRANGEMENT AND FEATURES

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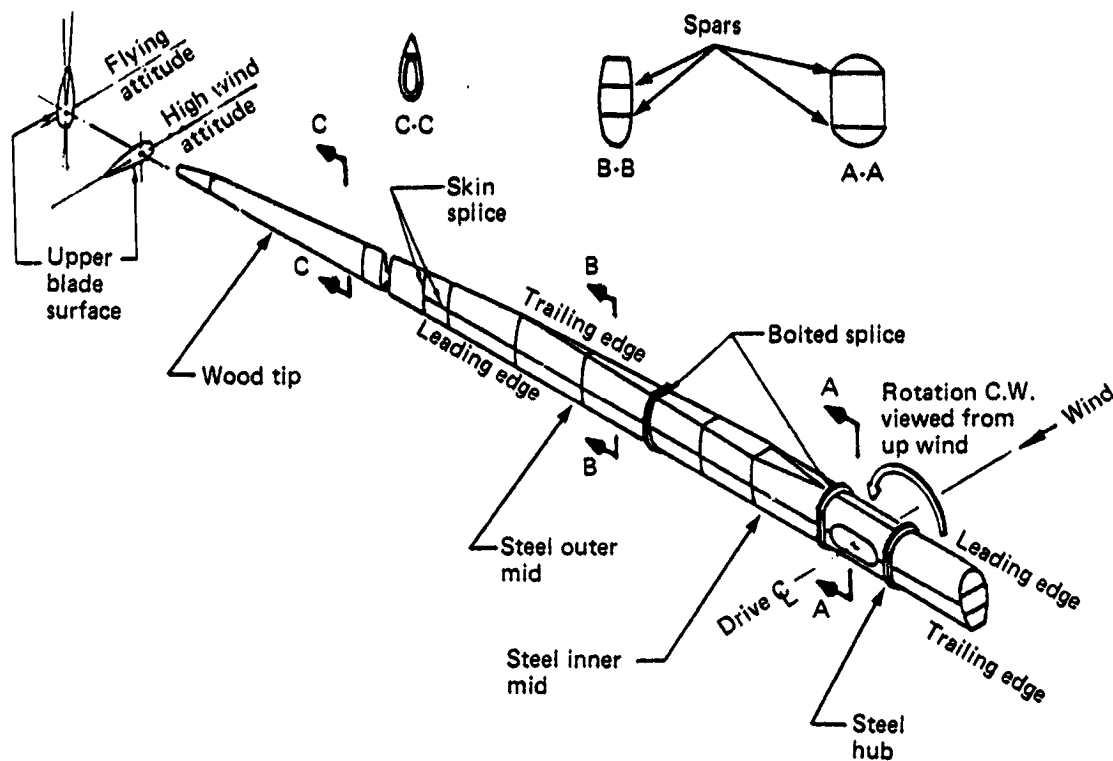


FIGURE 9. ROTOR BLADE CONFIGURATION

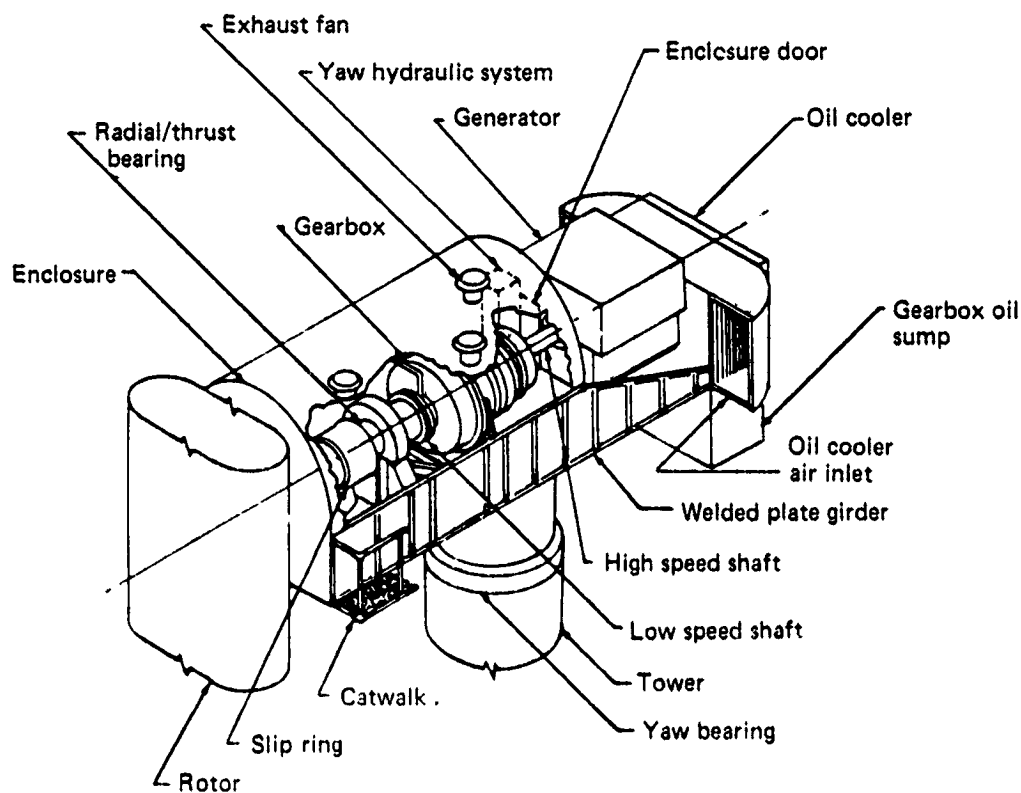


FIGURE 10. NACELLE ARRANGEMENT

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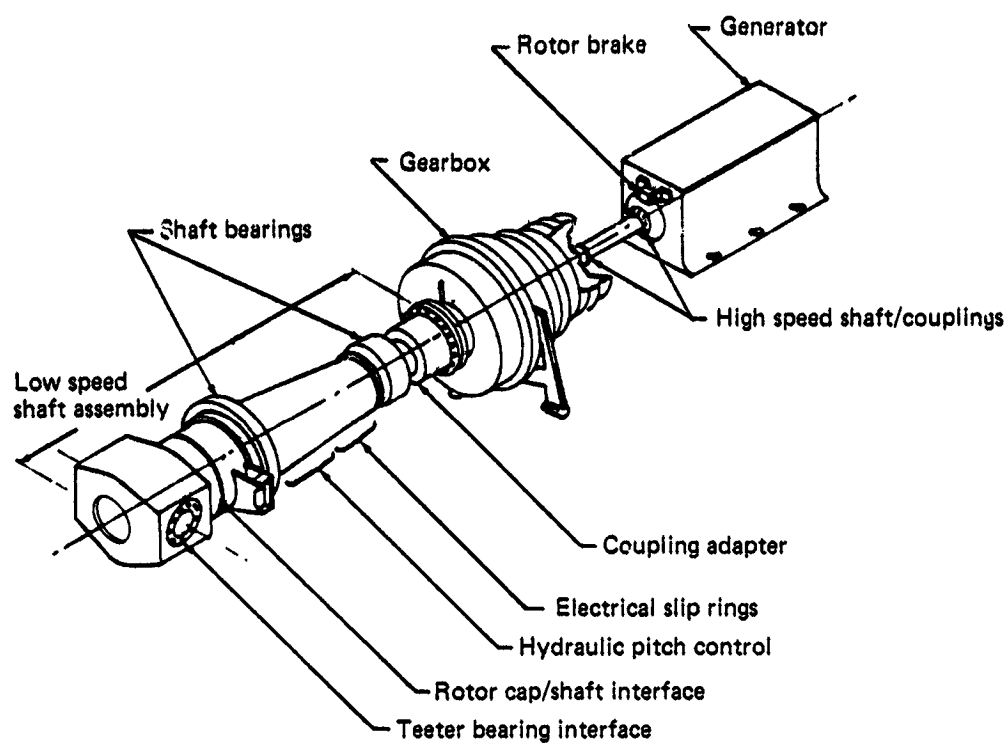


FIGURE 11. DRIVE TRAIN ARRANGEMENT

## QUESTIONS AND ANSWERS

R. R. Douglas

From: G. Doman

Q: Why did you not place your tower's first mode frequency below one per rev?

A: *Two reasons: 1) Our studies indicated such a tower is actually heavier and more expensive when designed to meet the high wind loads, and 2) with a variable speed generator system we would have been forced to operate part of the time near a 1/rev frequency. This is not a tolerable situation.*

From: M. Lotker

Q: Cost reduction (3 to 4¢/Kwhr) is small compared to utility costs. Does it really make sense to retool to Mod-5 or stick with and get high production on Mod-2?

A: *Reduction in cost of electricity between Mod-2 and Mod-5B is greater than the 25% indicated and is actually about 33%. This is not considered a small number by most potential customers! Secondly, there is no indication that elimination of the advancements represented by Mod-5B would permit high rate production of Mod-2.*

From: J. Glasgow

Q: Are any of these improvements (i.e. variable speed, etc.) going to be incorporated into future Mod-2 machines?

A: *As part of our internal R and D program, Mod-2 improvements are being continuously evaluated, some of which will almost certainly be incorporated in the future. At this time, there has not been a firm decision to incorporate variable speed generators into an improved Mod-2.*

From: B. Dahlroth

Q: Have you studied the cost effectiveness of concrete towers?

A: *We have looked at them only briefly on the basis that: 1) there is only a small reduction in the amount of steel required in a concrete tower as compared to our current tower because of the high tension loads, and 2) precise tailoring of stiffness is considerably more difficult with the combination of steel and concrete required in a concrete tower compared to steel alone in the current tower. Our judgment was that concrete offered no potential for cost reduction.*

R. R. Douglas (continued)

From: B. Barron

- Q: 1) What is the band width of the active control system in Mod-2?  
2) How is the pitch control system affected by use of the VSCF generator?

- A: 1) *One hertz.*  
2) *Neither the mechanical nor microprocessor control system hardware is changed as a result of variable speed. The software is modified to accommodate different speed ranges.*

From: M. Iriarte

- Q: Can you explain what you mean by a variable speed synchronous generator?

- A: *What we refer to as a variable speed synchronous flux generator is itself an induction type generator where the rotor speed plus the rotor excitation frequency relative to the rotor add up to give a synchronous excitation to the generator stator.*

From: P. Pekarul

- Q: What is the length of the tips?

- A: *As currently designed, the tips are 30% of rotor radius or 63 ft.*

From: L. Wendell

- Q: Does the active control system add significant wear and tear on the system?

- A: *Obviously, the design intent was to provide components that could supply relatively trouble-free service. The similar Mod-2 system has not indicated a problem to date. Mod-2 will be monitored for the next several years to assess actual experience, the results of which will be incorporated into Mod-5B if changes are found desirable.*

## WORKSHOP WRAP-UP REPORT

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At the end of each day, there was a discussion period led by the session chairmen for that day, with the authors and other interested attendees participating. The purpose was to allow the group to interact and see whether key issues of common concern would emerge from the discussions. The session chairmen provided me with their individual views of the discussions and I attended myself. These subjective inputs were the basis of this report.

No single issue of broad common concern emerged during the workshop. However, the discussions did indicate that the wind energy industry seems to be entering a new phase. There was specific concern for the long-term durability and reliability of turbines. This appears to have been sparked by the realization that mass-produced turbines may be operating on utility grids within a few years. In past workshops, the focus of interest was design and development related. Now, interest has shifted more toward designing for low-cost manufacturing and for operational requirements.

I have categorized and tabulated some of the specific ideas that I heard expressed as follows:

1. Design for low-cost manufacturing by:
  - selecting configurations which eliminate manufacturing problems and reduce costs.
  - verifying that the system has long-term durability and reliability by testing system, components, materials, and techniques.
  - obtaining design data for long-term fatigue life (over  $10^8$  cycles) on the basic materials, joints, fastening, and welds.

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2. Design for end user requirements by:
  - obtaining high availability and long life.
  - insuring fast and easy maintenance.
  - obtaining minimal environmental impact.
  - obtaining low installation cost.
  - realizing low COE.
3. Test wind turbine systems to:
  - verify COE.
  - demonstrate durability and reliability.
  - obtain maintenance requirements.
  - verify energy capture and land use required.
  - demonstrate environmental compatibility.
4. Verify and improve design tools by:
  - operating prototype machines in a testing mode to check the dynamic and aerodynamic modeling.
  - running specific tests aimed at improving the tools for operating conditions and configurations where improved predictive capability is required.
5. Reduce institutional constraints by:
  - consolidating the multiple overlapping permit requirements for wind turbine installation and operation. (One-stop permit shopping is highly desirable.)
  - defining the future role and specific activities of the federal government in the wind industry.

In conclusion, there were no key issues of common concern for the majority of participants; however, there was concern expressed by various individuals for a broad range of issues that I have attempted to summarize in the above tabulation. I suspect that this diversity of concerns is, in part, due to the wide spectrum of participant backgrounds and interests. The group covered all sectors of the wind industry from designers and dynamic analysts to utility planners and financial analysts.